DIRECTOR OF CENTRAL INTELLIGENCE
Security Committee

SECOM-D-292
22 November 1977

MEMORANDUM FOR: Executive Secretary, NFIB

25X1 FROM: [redacted]
Acting Chairman

SUBJECT: National Technical Threat Estimating Guide--Carrier Current Transmitter (C) Estimating Guide RD/3-76 (U)

25X1 1. [redacted] This memorandum forwards the subject report on carrier current transmitters for the information of the Board. The report provides the detailed technical backup to the previously distributed report, National Technical Threat Estimates 1976-1981.

25X1 2. [redacted] This guide is intended to provide the basic theoretical and factual foundation necessary to make sound technical estimates of the technical surveillance threat both for normal and unusual conditions. The guide is expected to be used primarily by technical and engineering personnel in the conduct of detailed technical studies. It will also facilitate preparation of updated estimates as they become required.

25X1 3. [redacted] For additional copies, NFIB members should contact their representative on the DCI Security Committee's Research and Development Subcommittee or Mr. [redacted] 25X1

[redacted] 25X1

Attachment:
Threat Estimate
(28 copies)

63417

DIRECTOR OF CENTRAL INTELLIGENCE
Security Committee
RESEARCH AND DEVELOPMENT SUBCOMMITTEE

8 NOV 1977

MEMORANDUM FOR: Chairman, Security Committee

SUBJECT : National Technical Threat Estimating Guide, Carrier Current Transmitter (C) Estimating Guide RD/3-76 (U)

25X1 1. [redacted] Attached for your use and retention is the report, National Technical Threat Estimating Guide, Carrier Current Transmitter. This report provides the detailed technical backup to the previously distributed report, National Technical Threat Estimates 1976-1981. This technical threat estimating guide is intended to provide the basic theoretical and factual foundation necessary to make sound technical estimates of the technical surveillance threat both for normal and unusual conditions. The estimating guide is expected to be used primarily by technical and engineering personnel in the conduct of detailed technical studies. This guide will also facilitate preparation of updated technical threat estimates as they become required.

25X1 2. [redacted] Other on-going studies will relate this technical threat to specific intelligence service capabilities insofar as they are known. Additional copies of this report are available upon request through each member agency's representative on the Research and Development Subcommittee or from the Executive Secretary, Research and Development Subcommittee.

25X1 3. [redacted] You may wish to forward this report to the NFIB for noting.

[redacted] 25X1

Chairman
Research and Development
Subcommittee

Attachment:
As stated

CL BY [redacted] 25X1
E2 IMPDET

SUBJECT: National Technical Threat Estimating Guide--Carrier Current Transmitter (C) Estimating Guide RD/3-76 (U)

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Secret

25X1

DIRECTOR
OF
CENTRAL
INTELLIGENCE

DCI Security Committee
Technical Surveillance
Countermeasures Subcommittee
Research & Development Subcommittee

National Technical Threat Estimating Guide—
Carrier Current Transmitter (C)
Estimating Guide RD/3-76 (U)

Secret

RD/3-76
November 1976

No 13

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ESTIMATE

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ESTIMATING GUIDE

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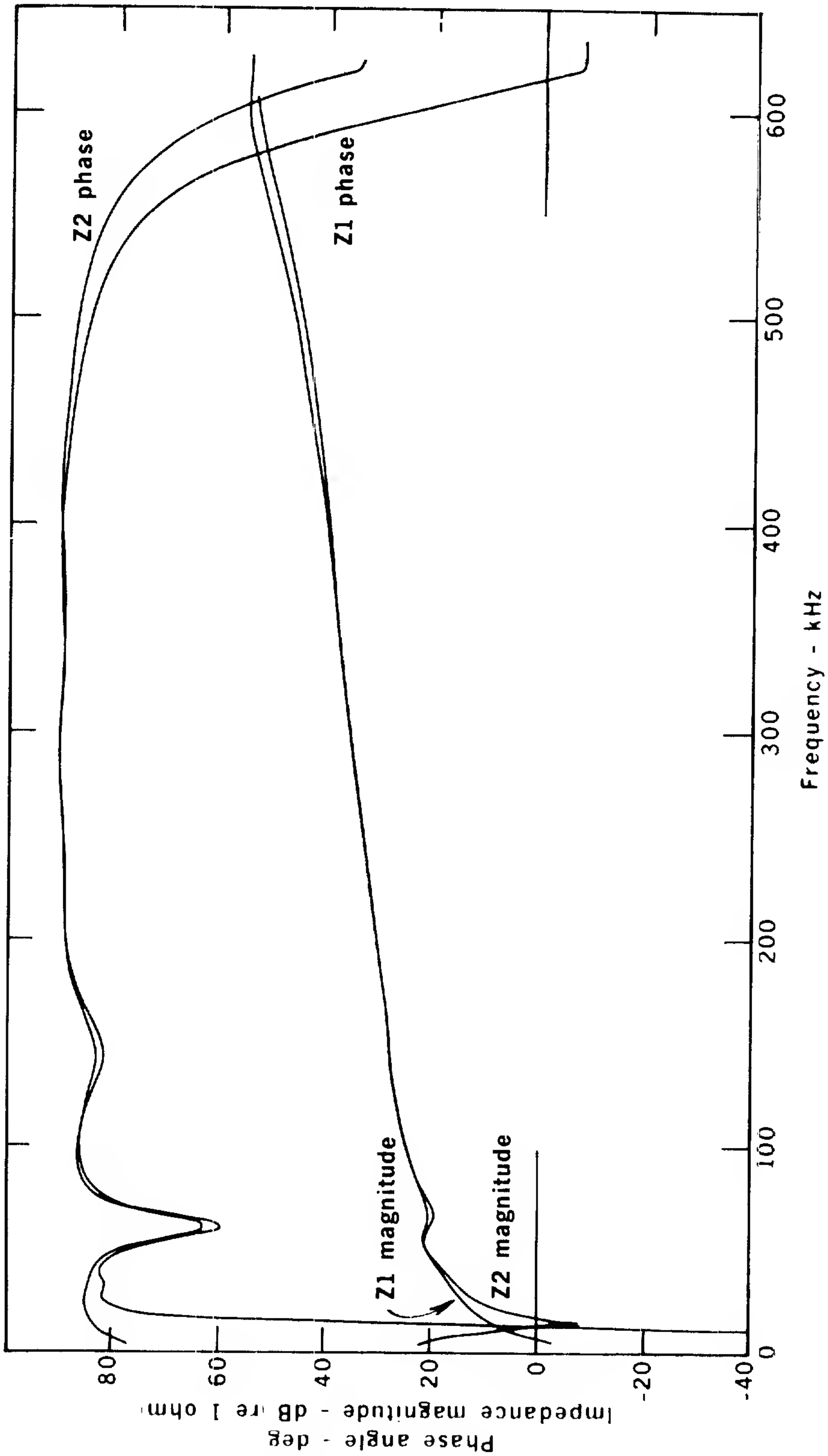

Figure 2. Transformer impedance

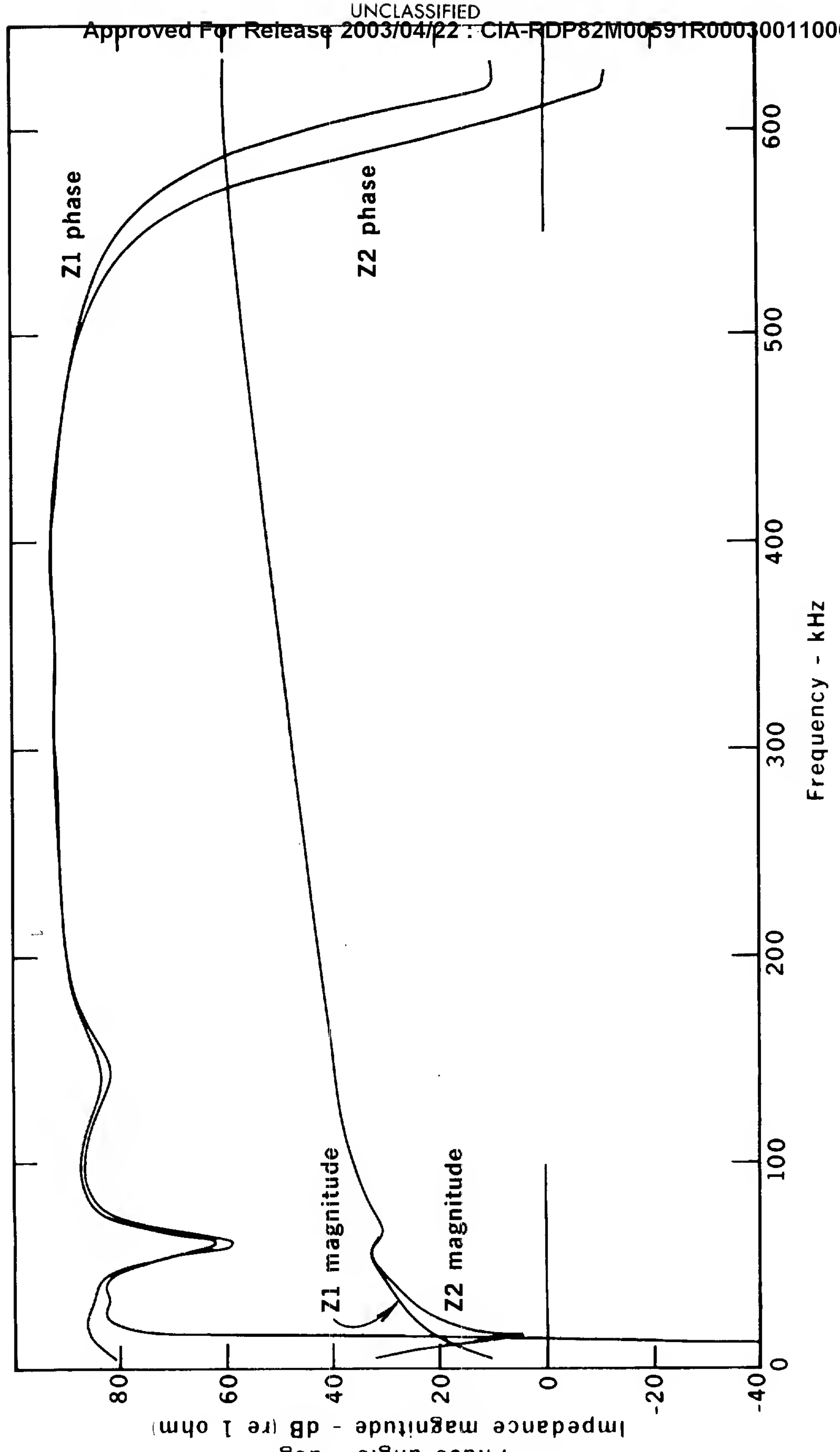

Figure 3. Transformer impedance

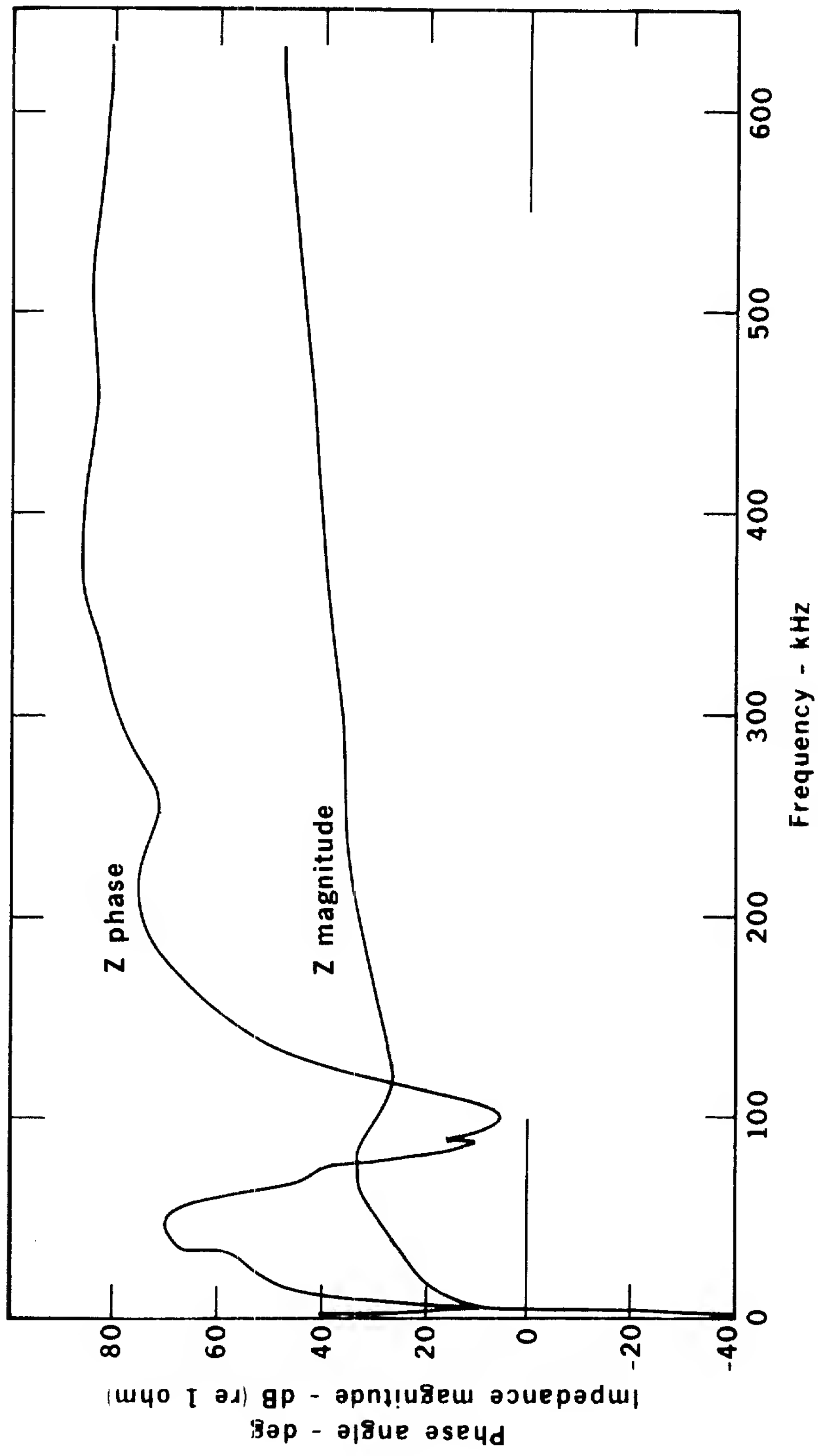

Figure 4. Location 3—Impedance, floor 10, outlet B-16 (red phase-high to neutral)

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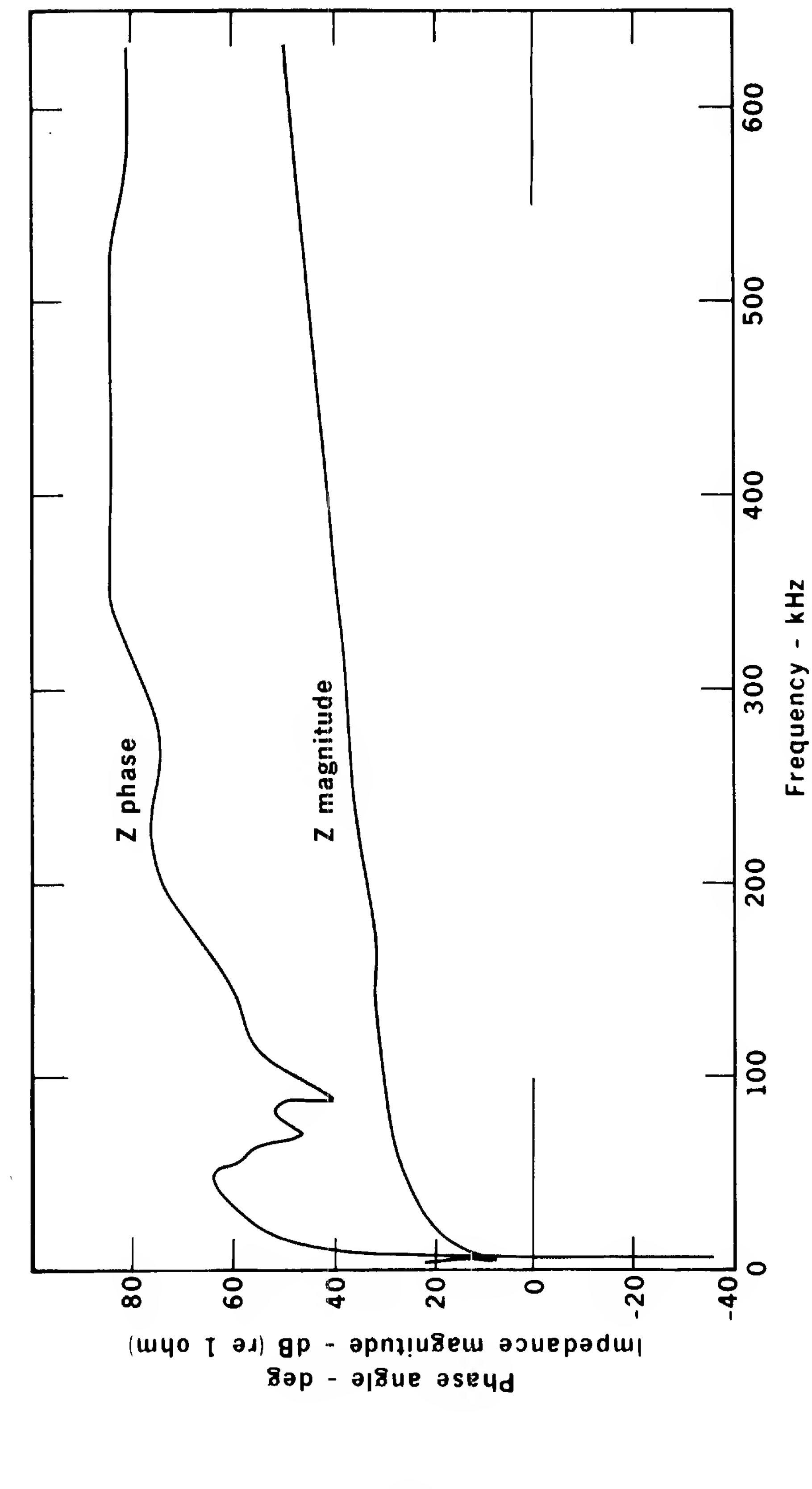

Figure 5. Location 3—Impedance, floor 10, outlet B-18 (blue phase-high to neutral)

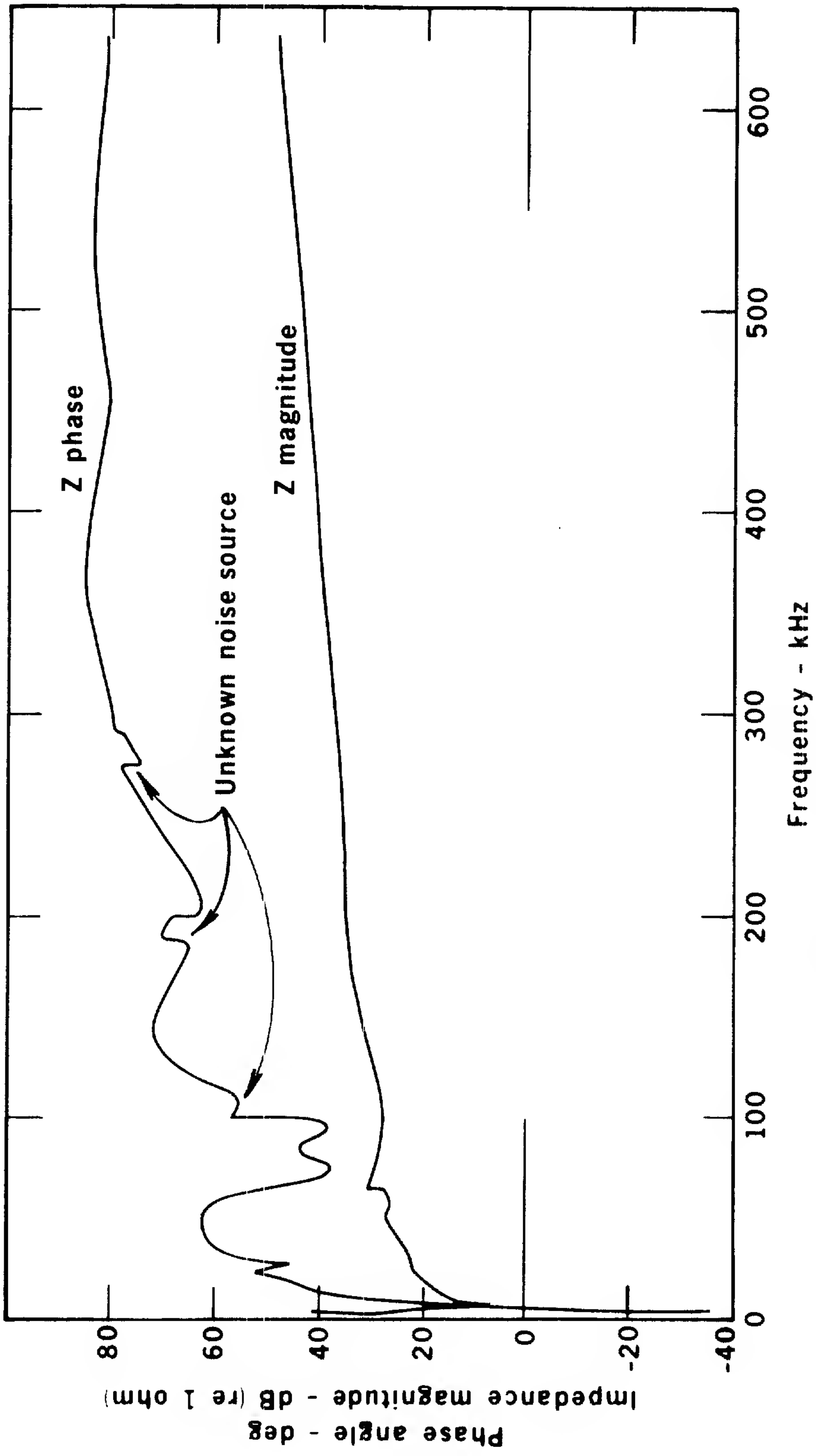

Figure 6. Location 3—Impedance, floor 10, outlet B-14 (black phase-high to neutral)

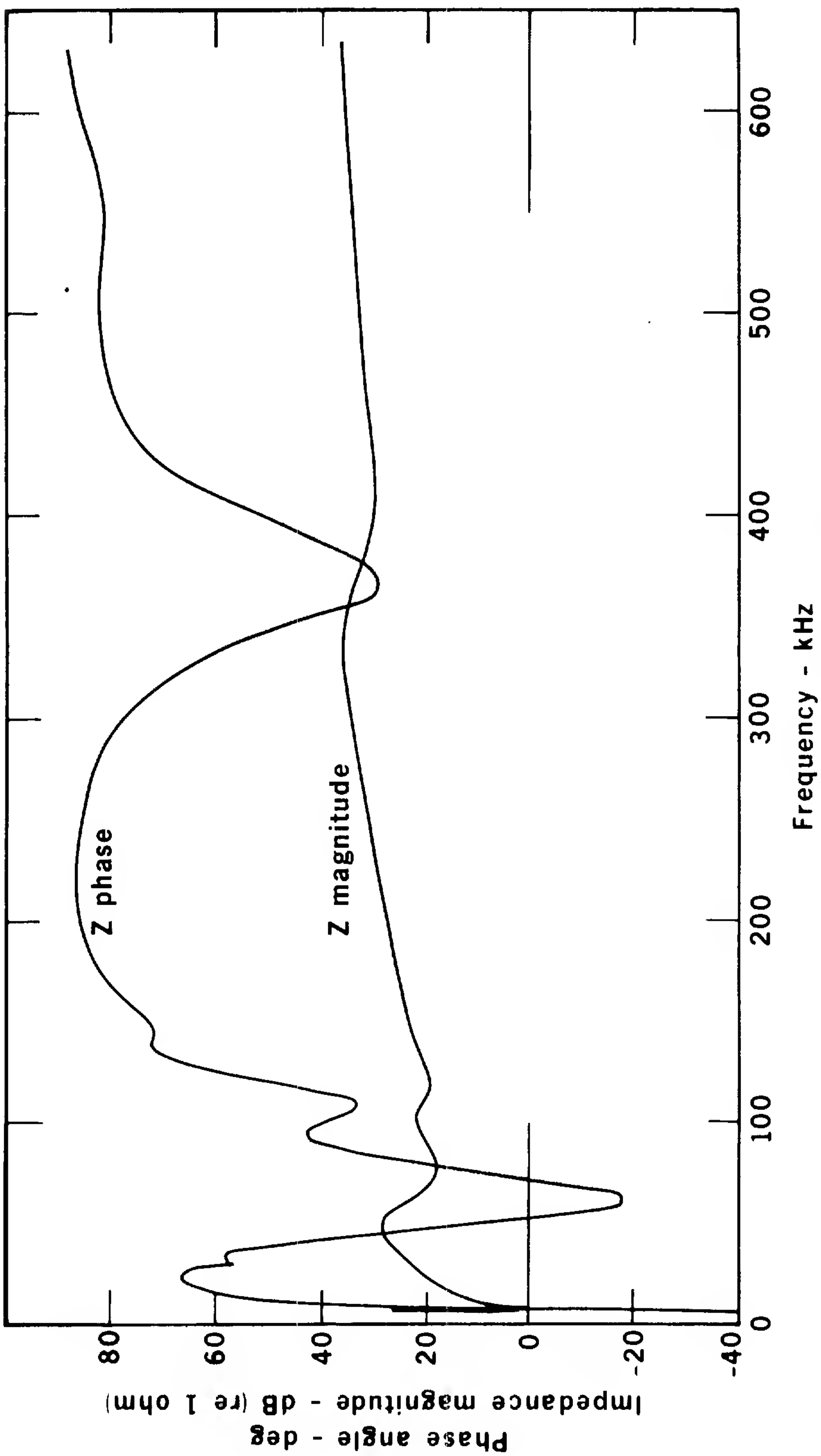

Figure 7. Location 1—Utility impedance, A side, active

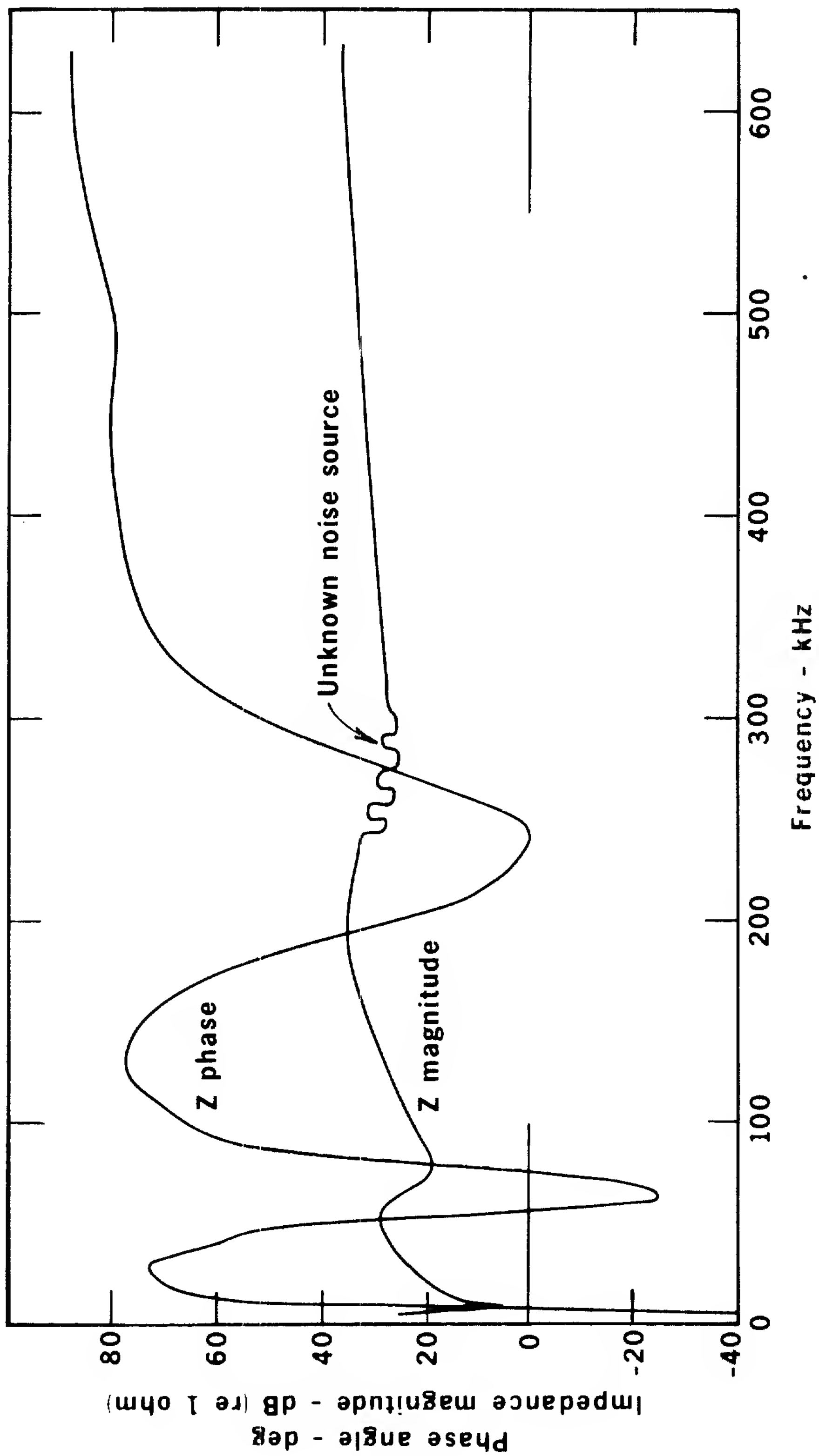

Figure 8. Location 1—Utility impedance, B side, active

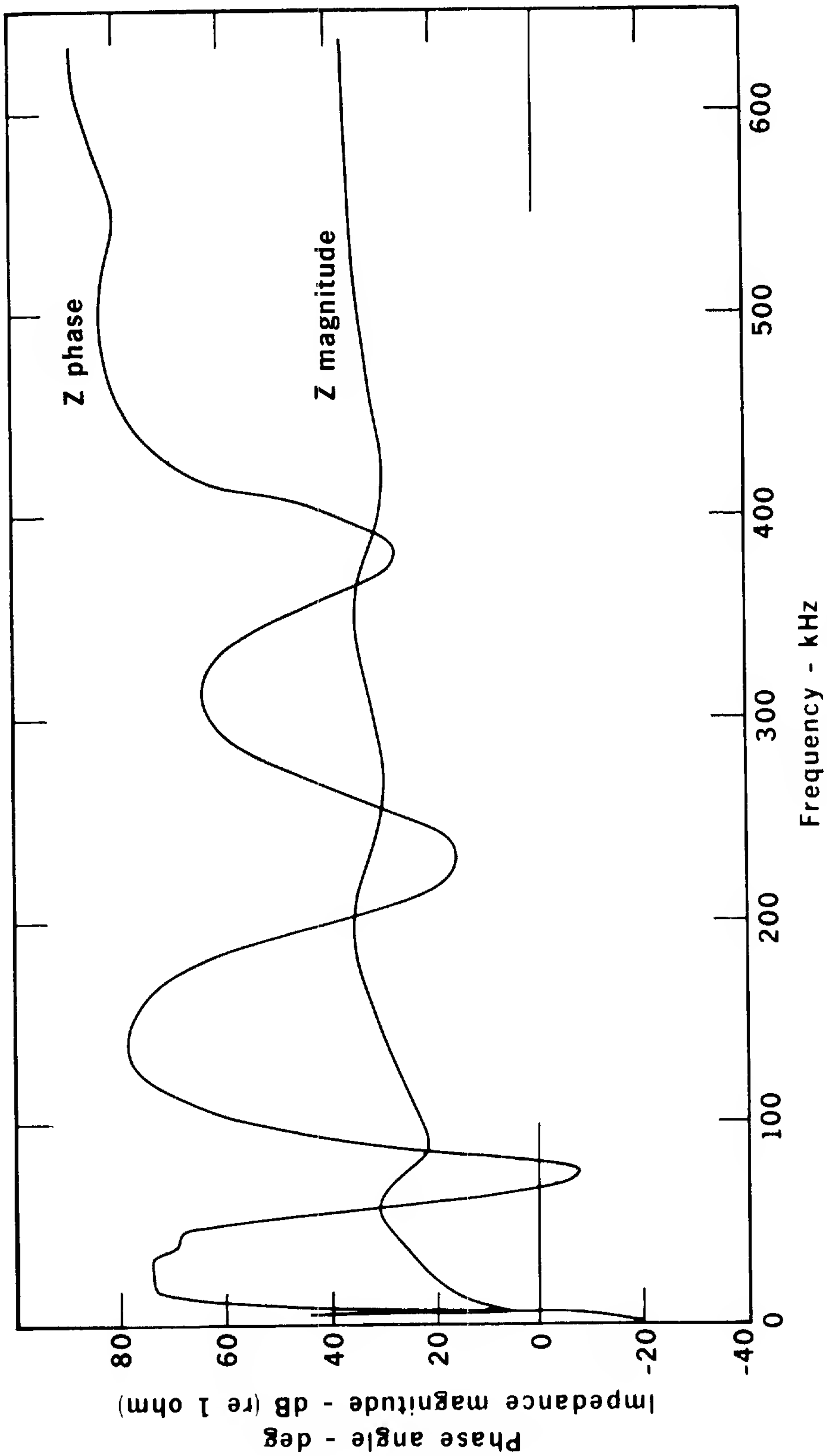

Figure 9. Location 1—Utility impedance, sides B to A, active

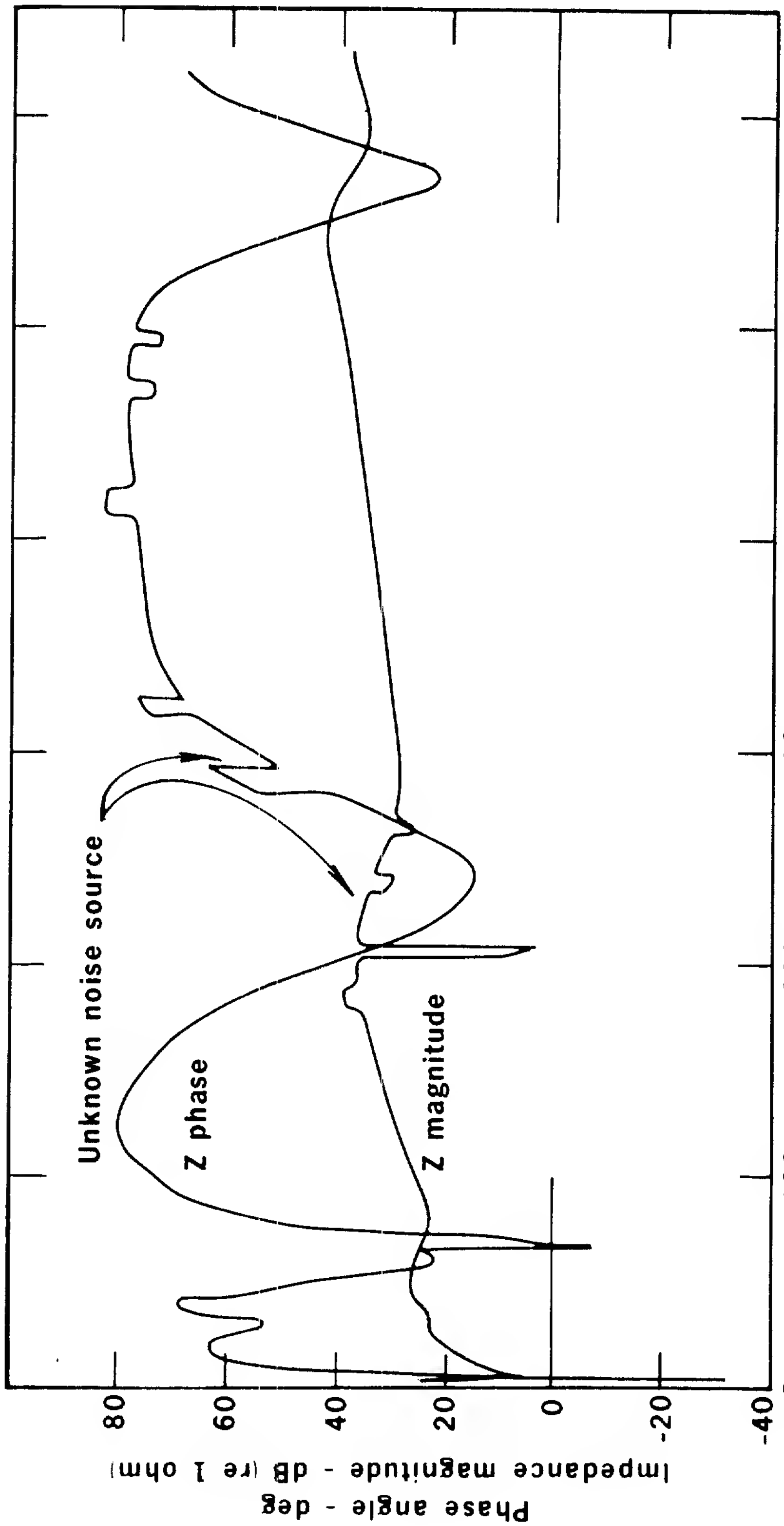

Figure 10. Location 1—Impedance, outlet 3-2 (B side), active; no loads; all breakers closed

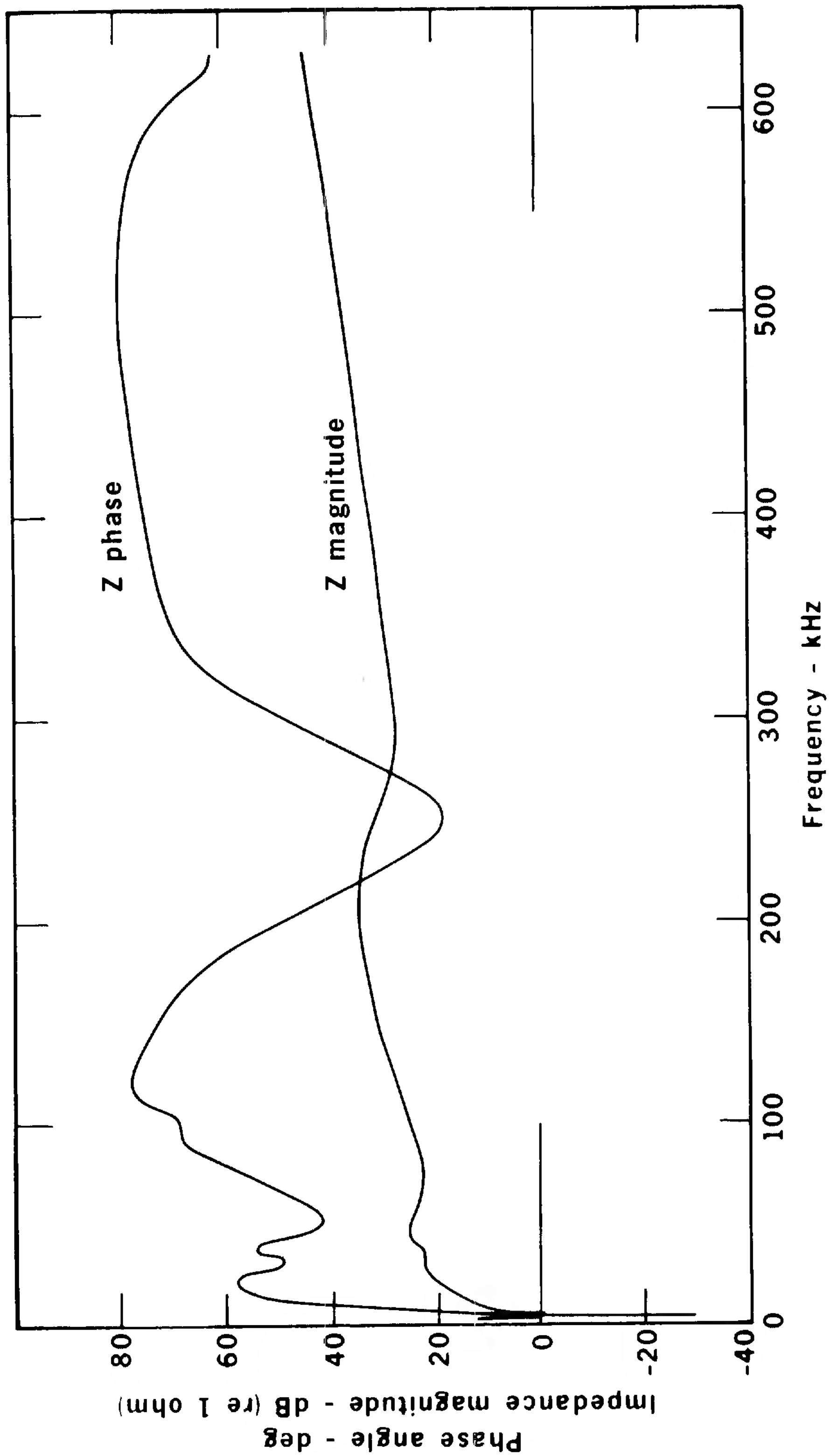

Figure 11. Location 1—Impedance, outlet 3-2 (B side), active; all breakers closed; load: garage door opener connected but not operating on outlet 3-8

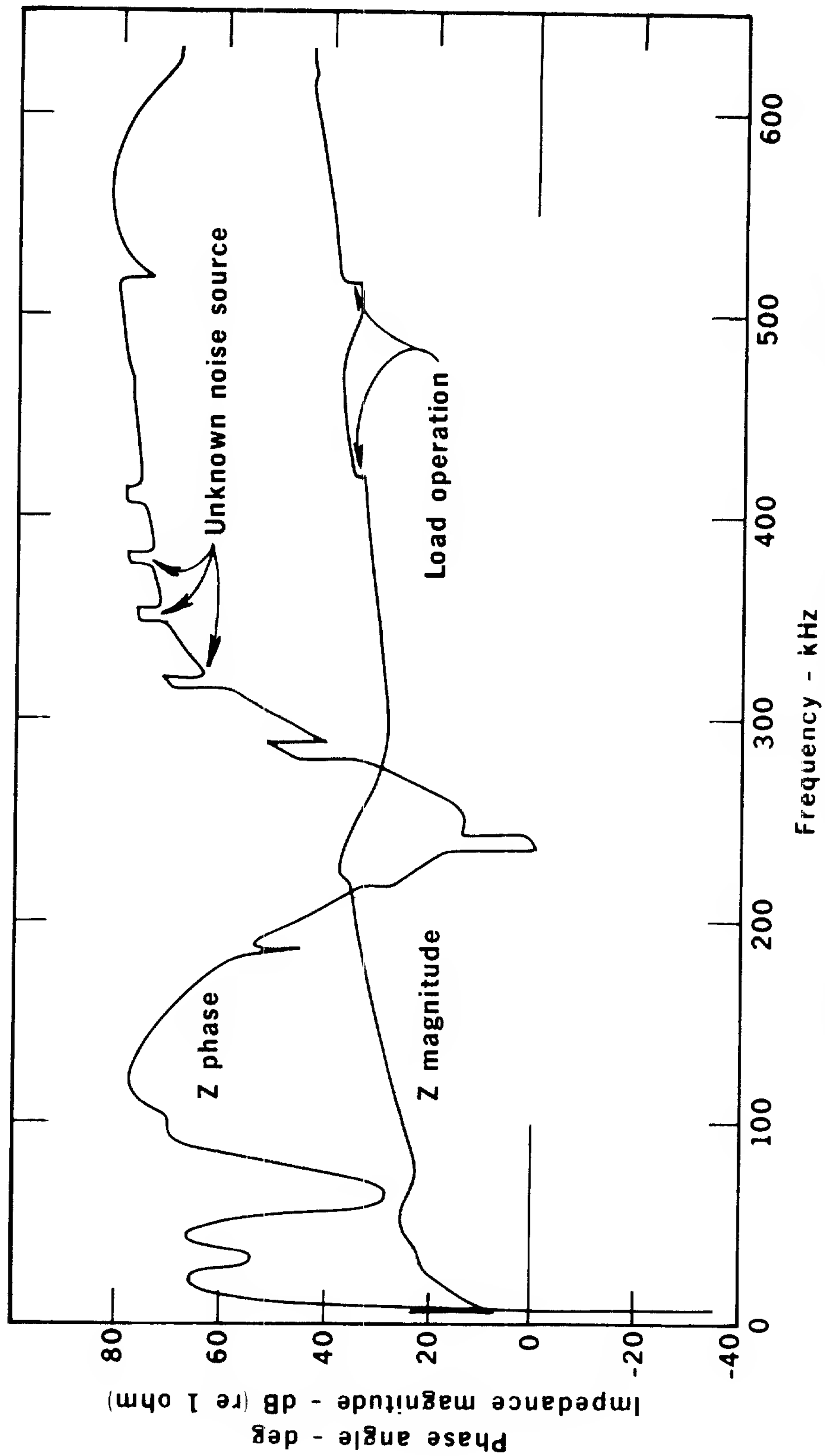

Figure 12. Location—Impedance, outlet 3-2 (B side), active, loaded; all breakers closed; load: garage door opener operated every 100 kHz on outlet 3-3

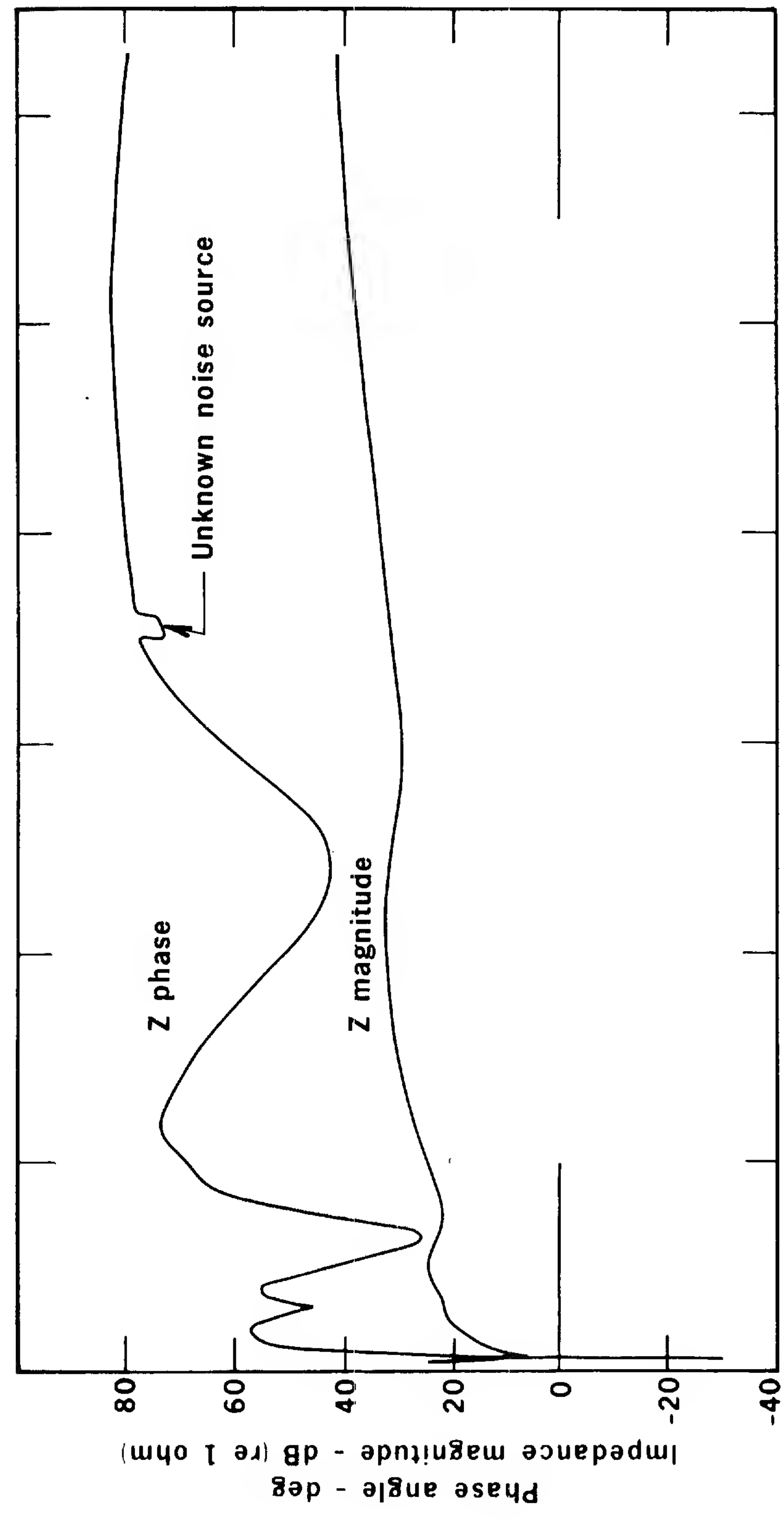

Figure 13. Location 1—Impedance, outlet 3-2 (B side), active, loaded; all breakers closed; load: 3-100 W lamps on outlet 1-6 (B side)

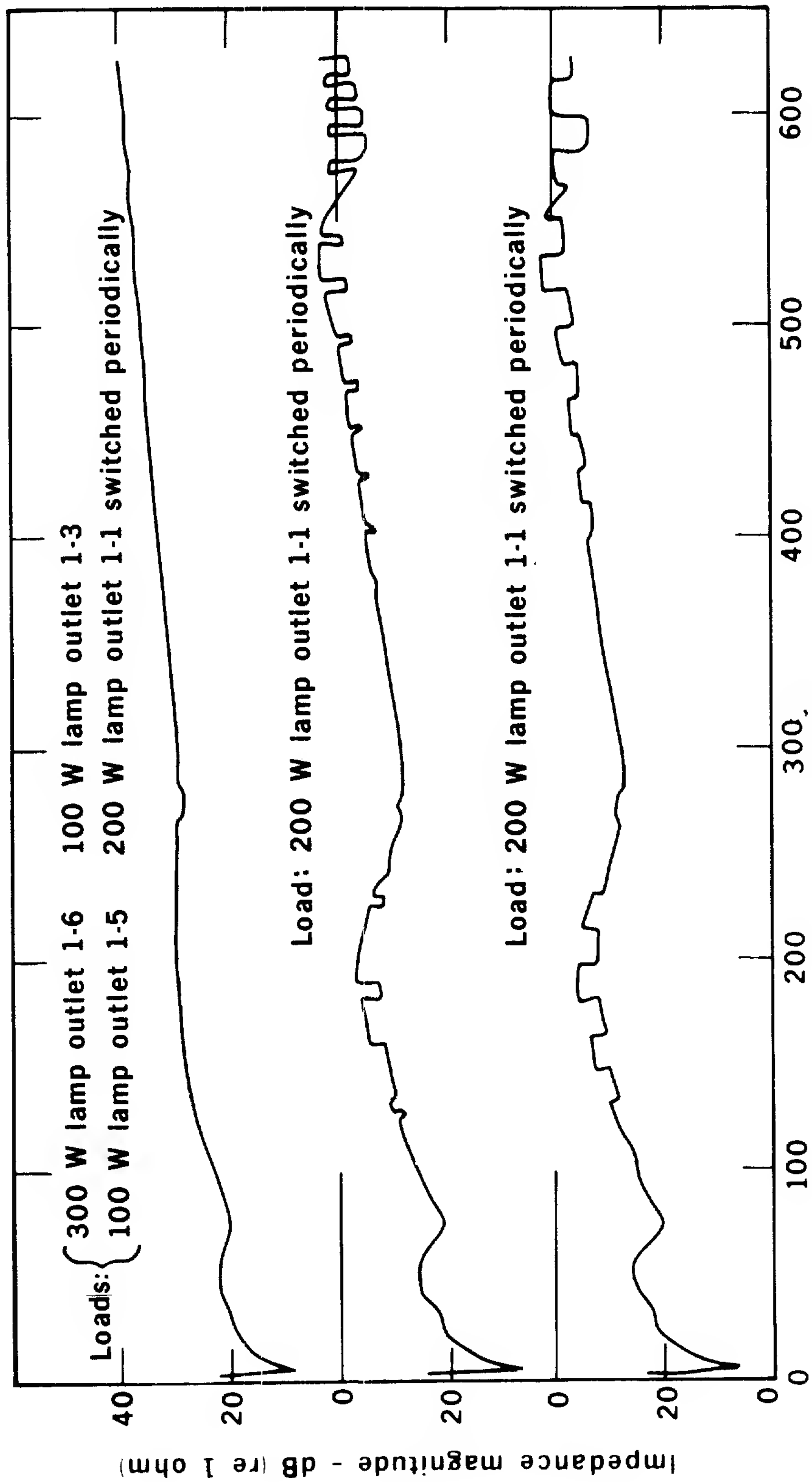

Figure 14. Location 1—Impedance magnitude, outlet 3-2 (B side), incandescent lamp loads; all breakers closed; on circuit 1 (B side)

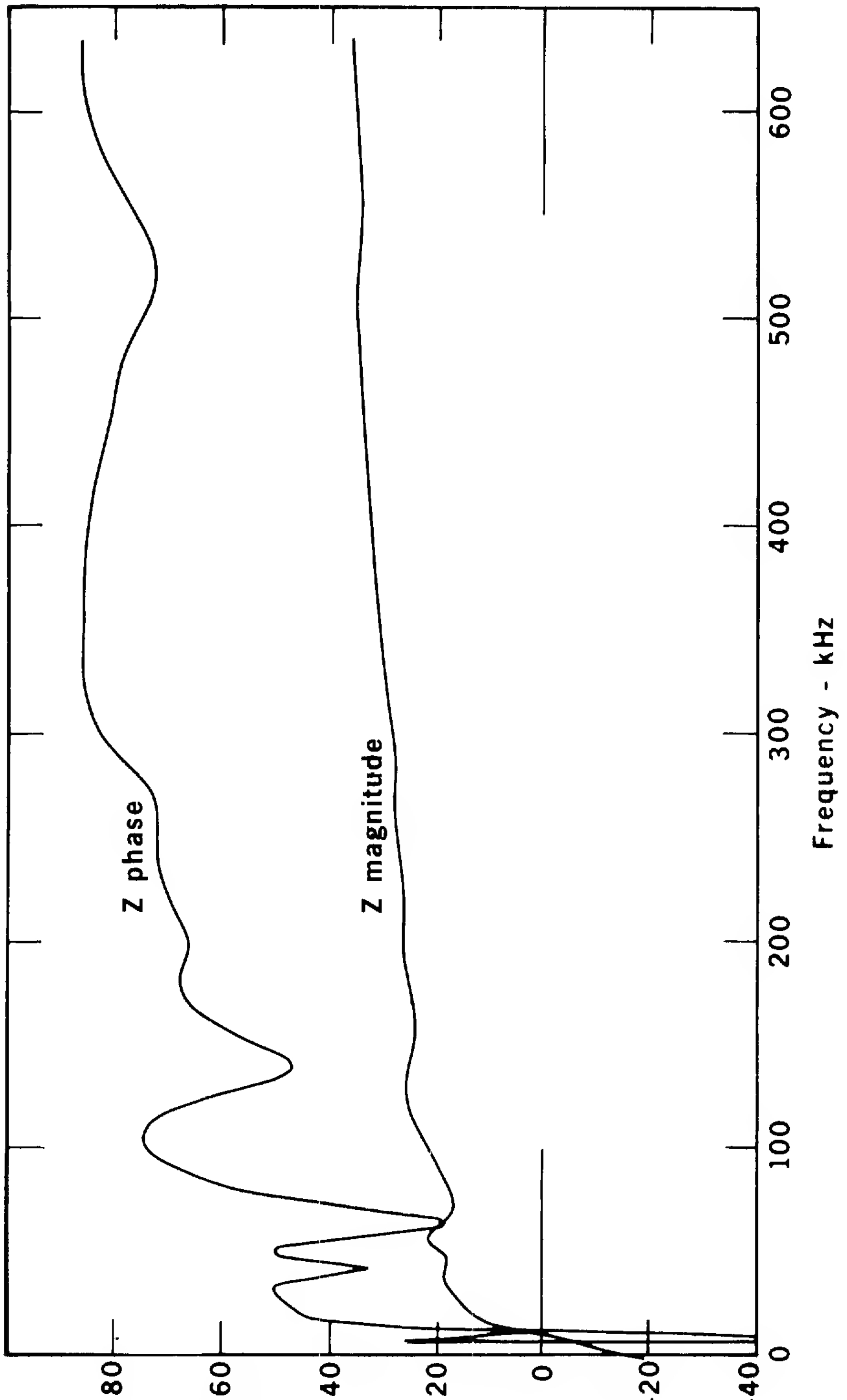

Figure 15. Location 2—Utility impedance, A side; main breakers open

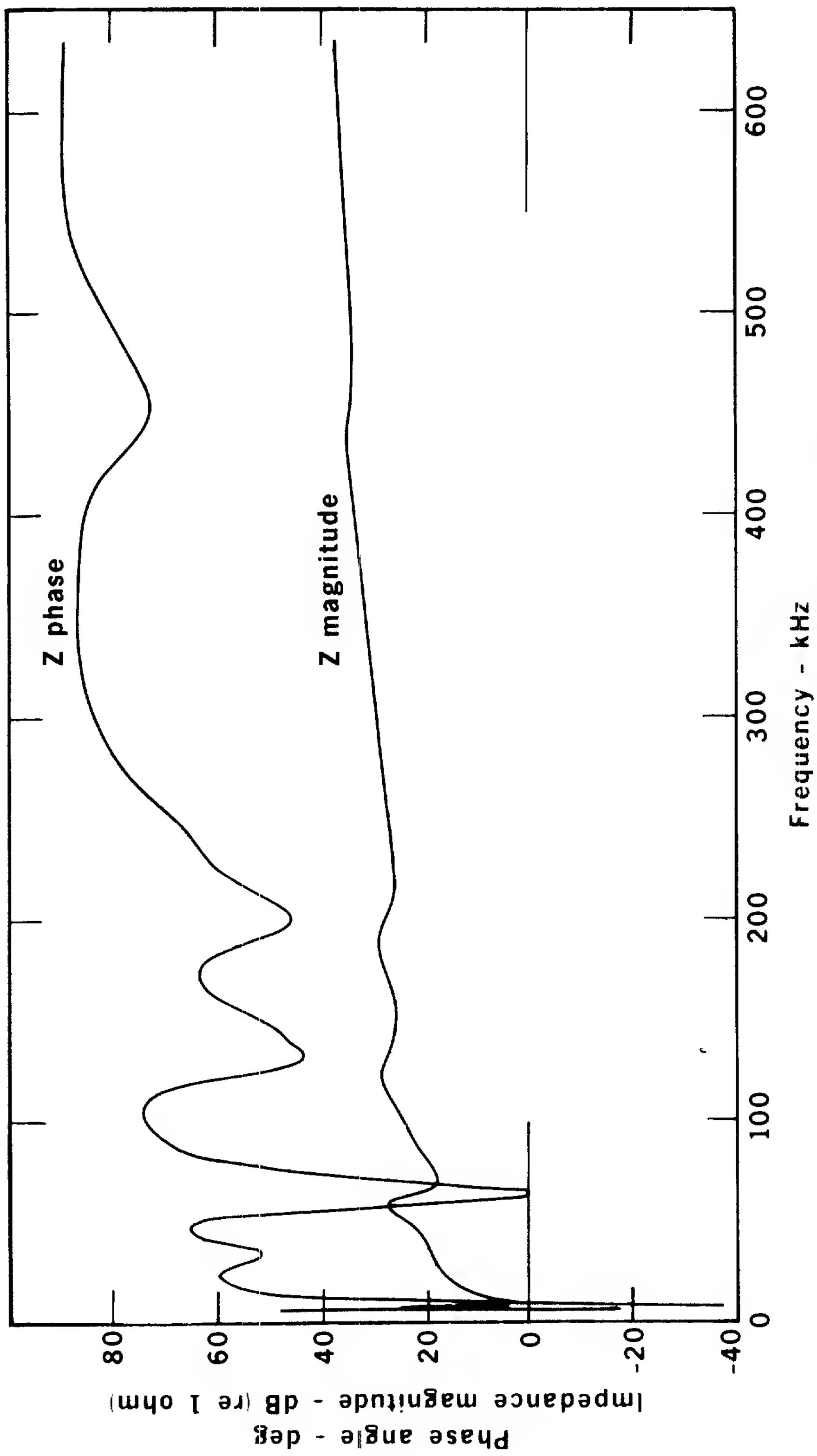

Figure 16. Location 2—Utility impedance, A side to B side; main breakers open

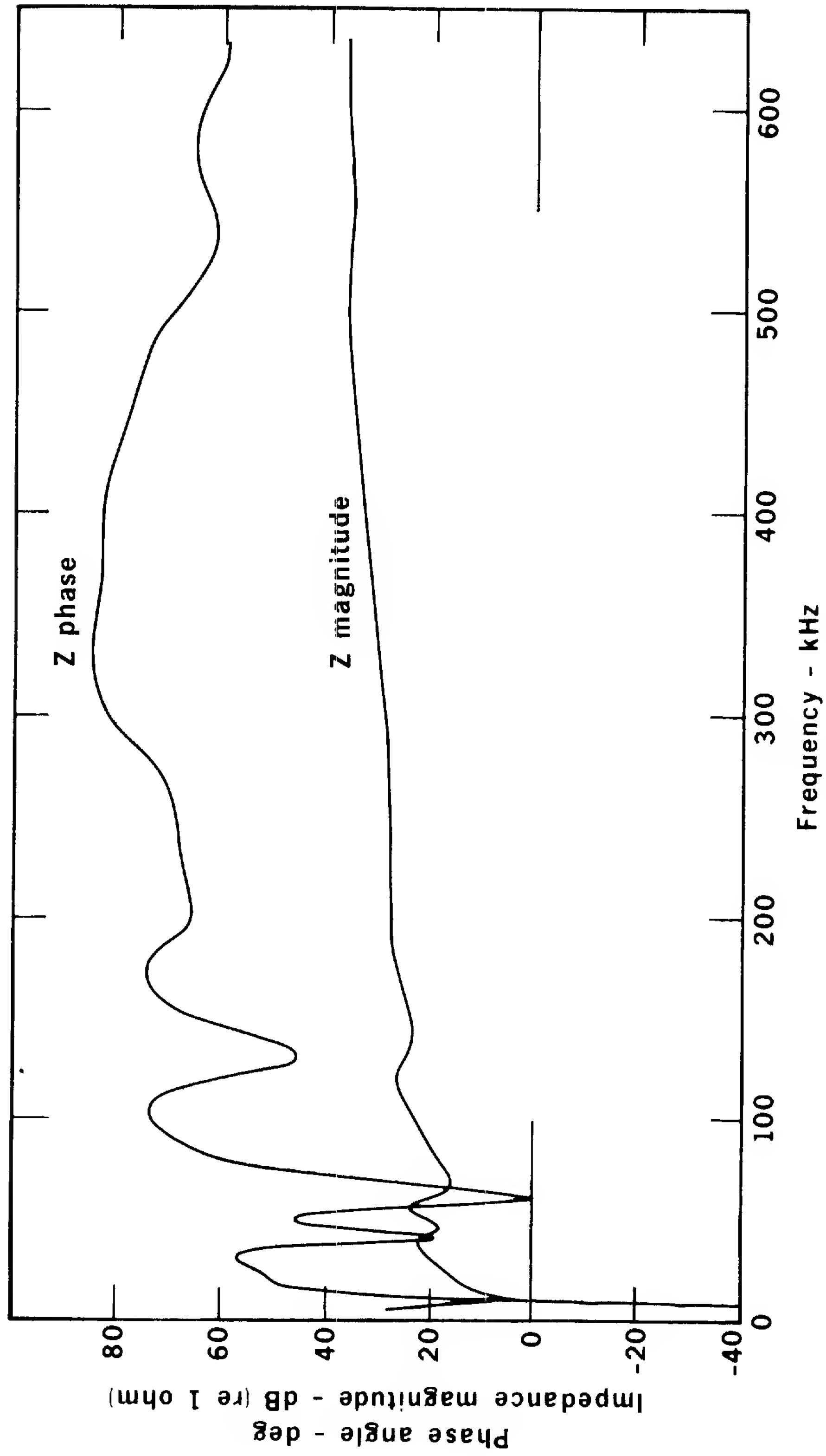

Figure 17. Location 2—Impedance, A side, loaded; measured at breaker box; air conditioner on (circuit 4-A side)

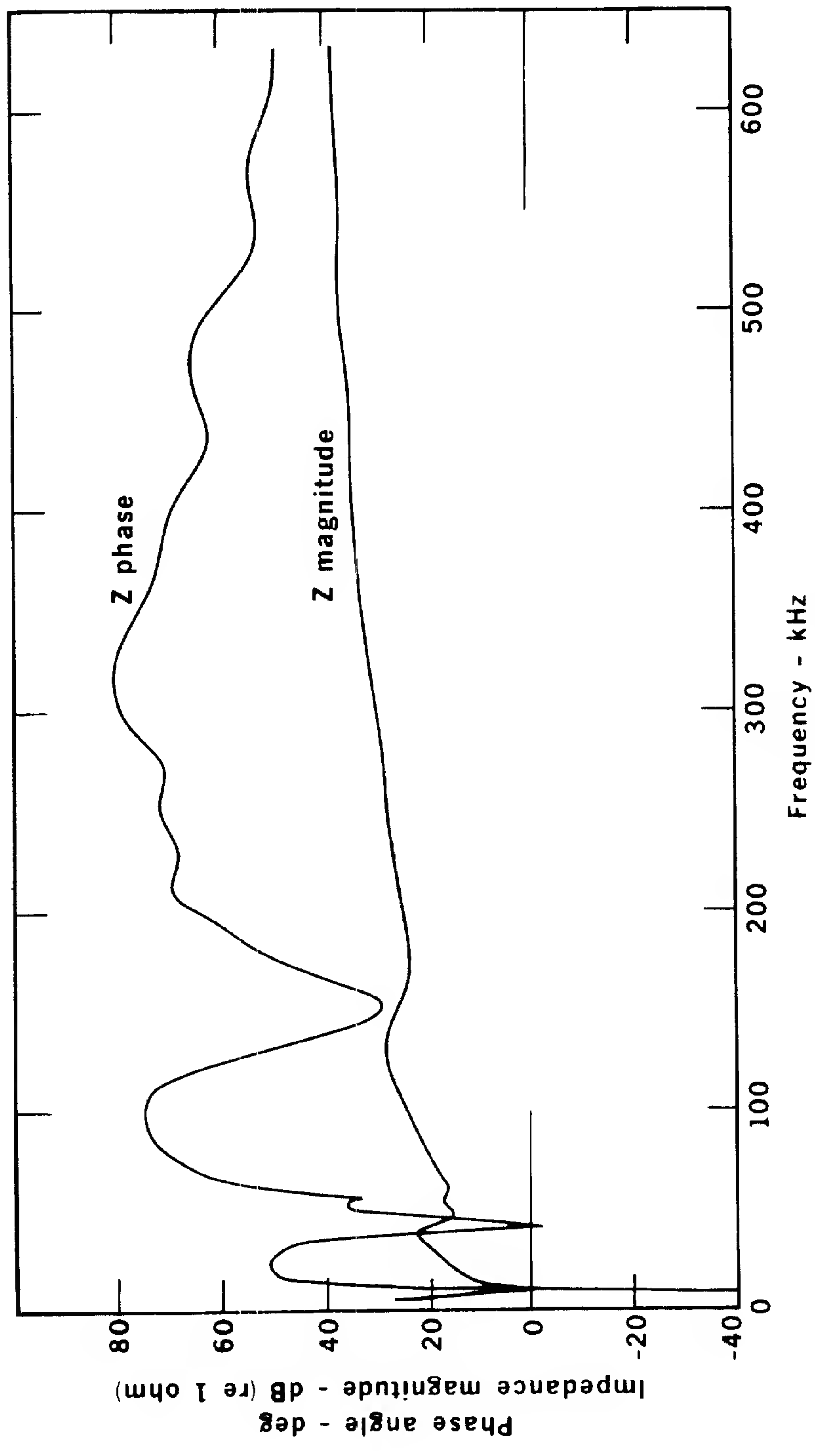

Figure 18. Location 2—Impedance, B side, loaded; measured at breaker box; air conditioner on (circuit 4-A side)

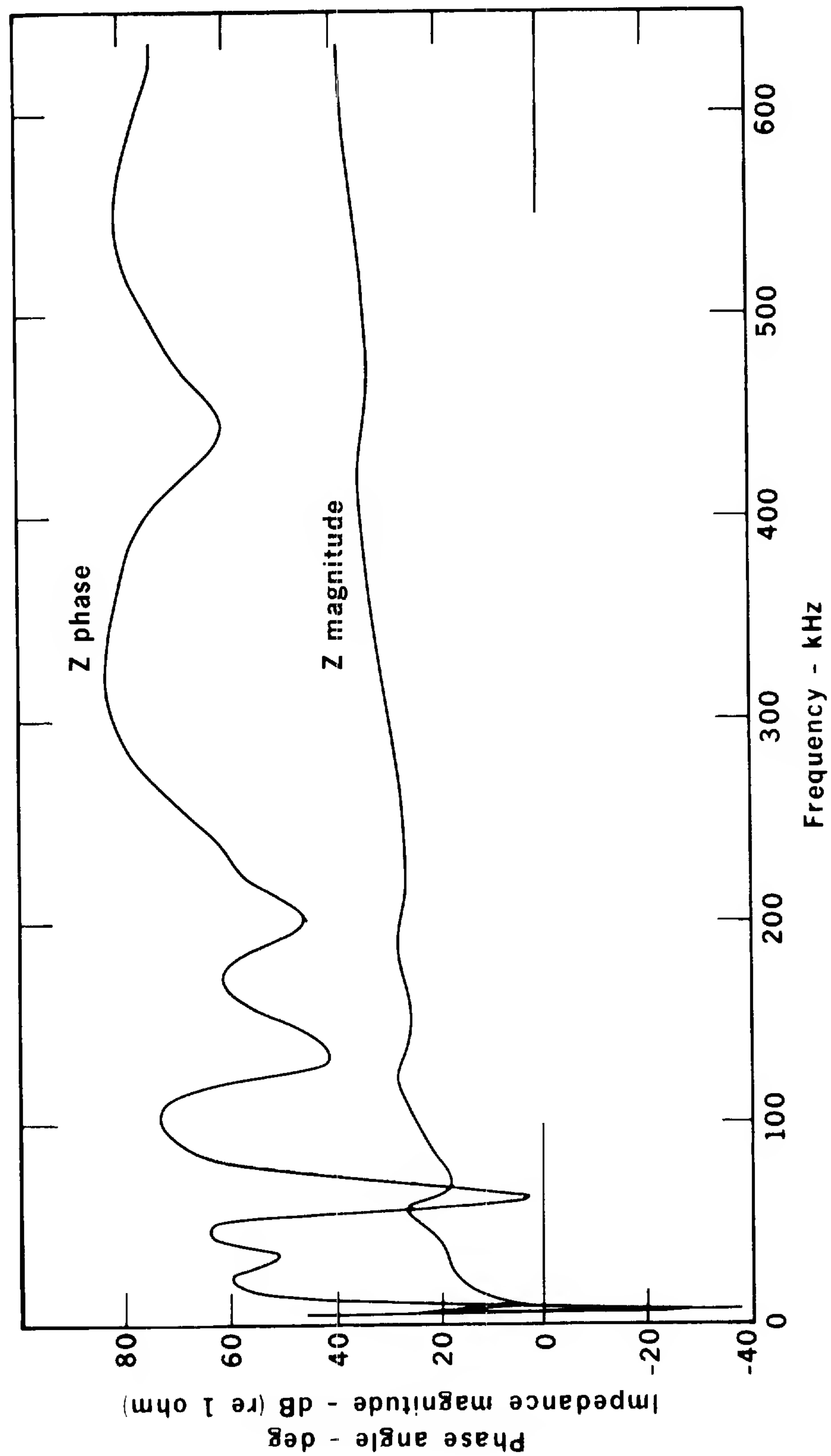

Figure 19. Location 2—Impedance, A side to B side, loaded; measured at breaker box; air conditioner on (circuit 4-A side)

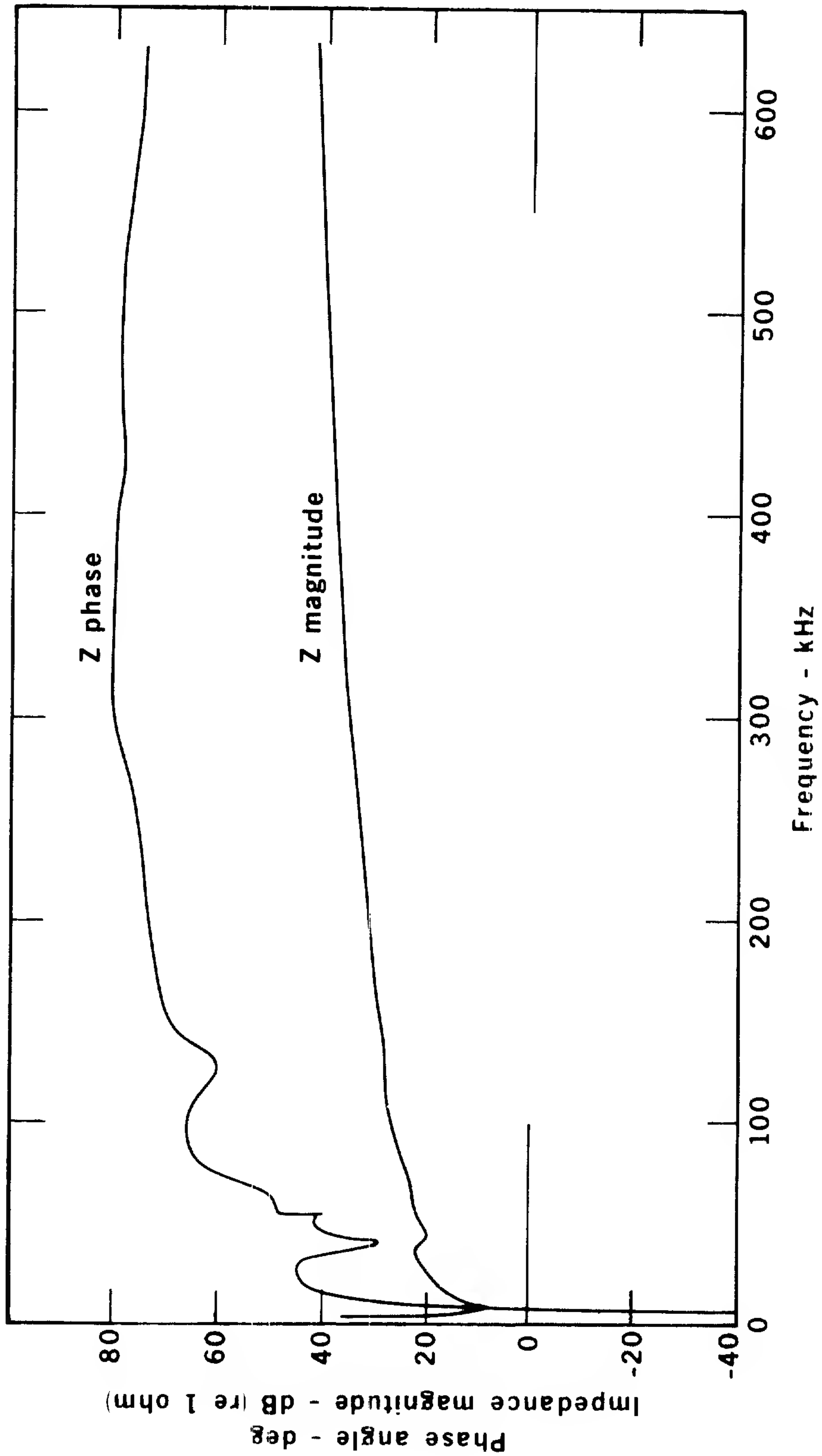

Figure 20. Location 2—Impedance, outlet 9-6, all breakers closed

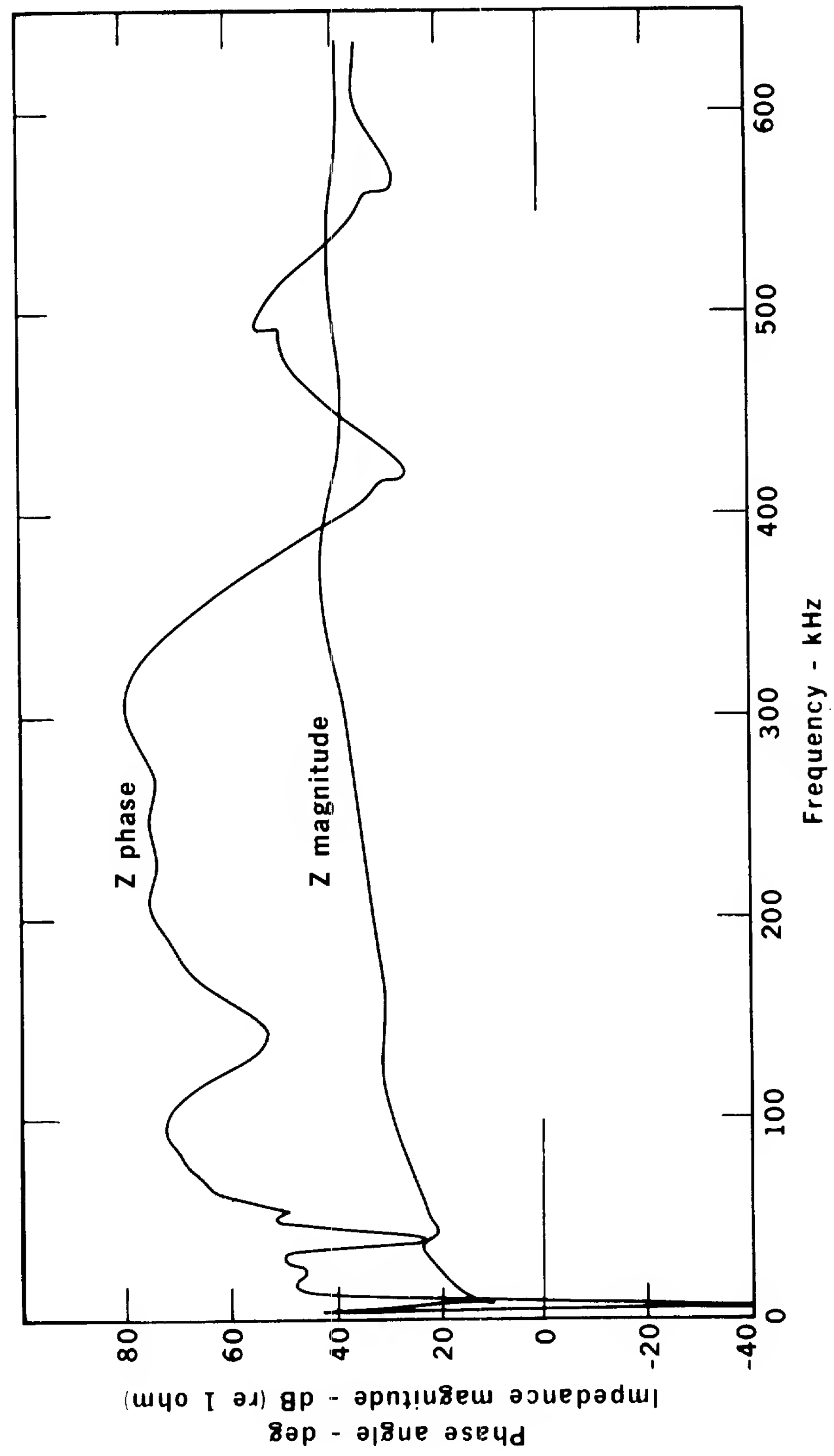

Figure 21. Location 2—Impedance, outlet 10-5

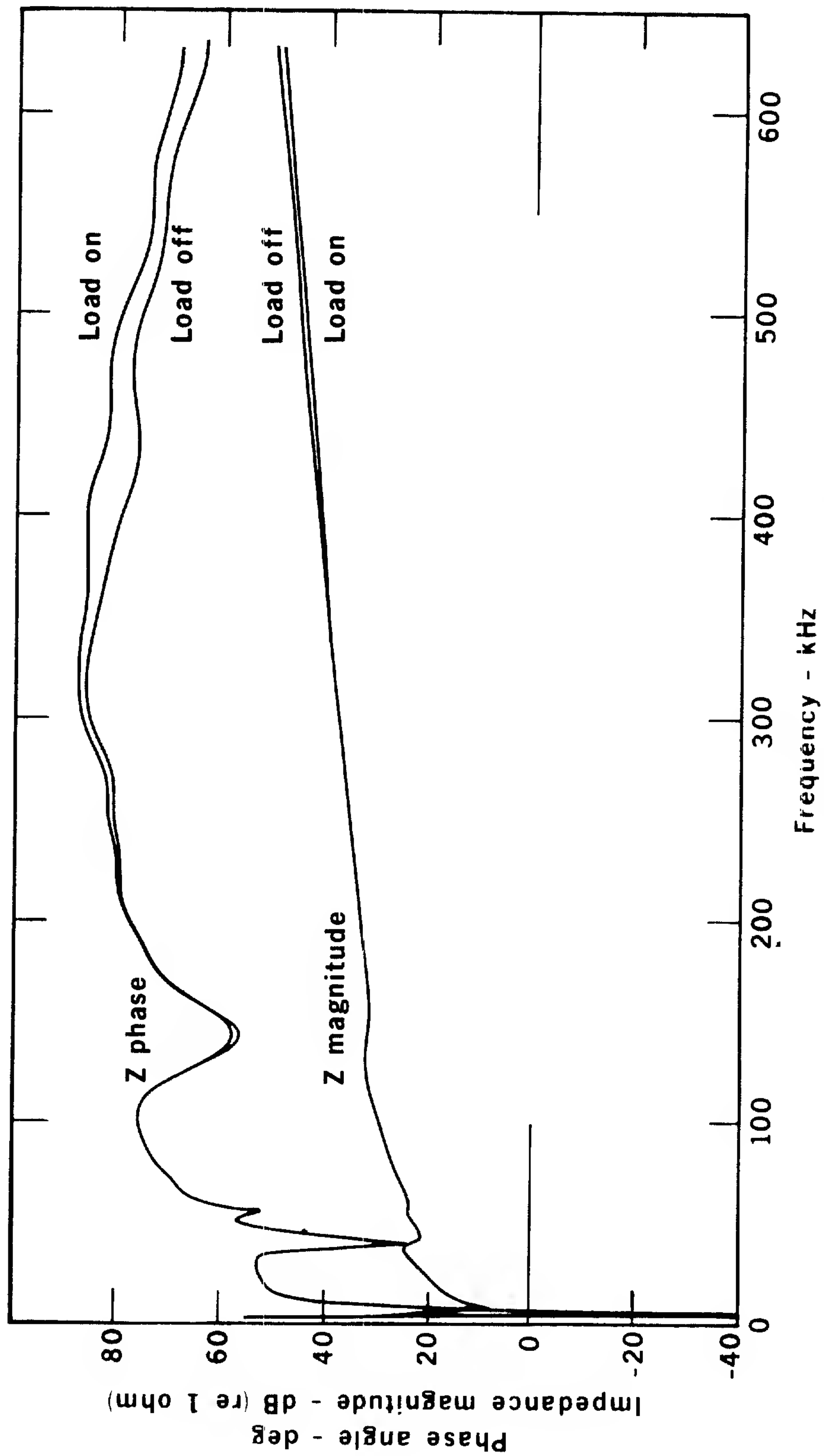

Figure 22. Location 2—Impedance, outlet 4-6; all breakers open except circuit 4; load, furnace fan on outlet 4-6

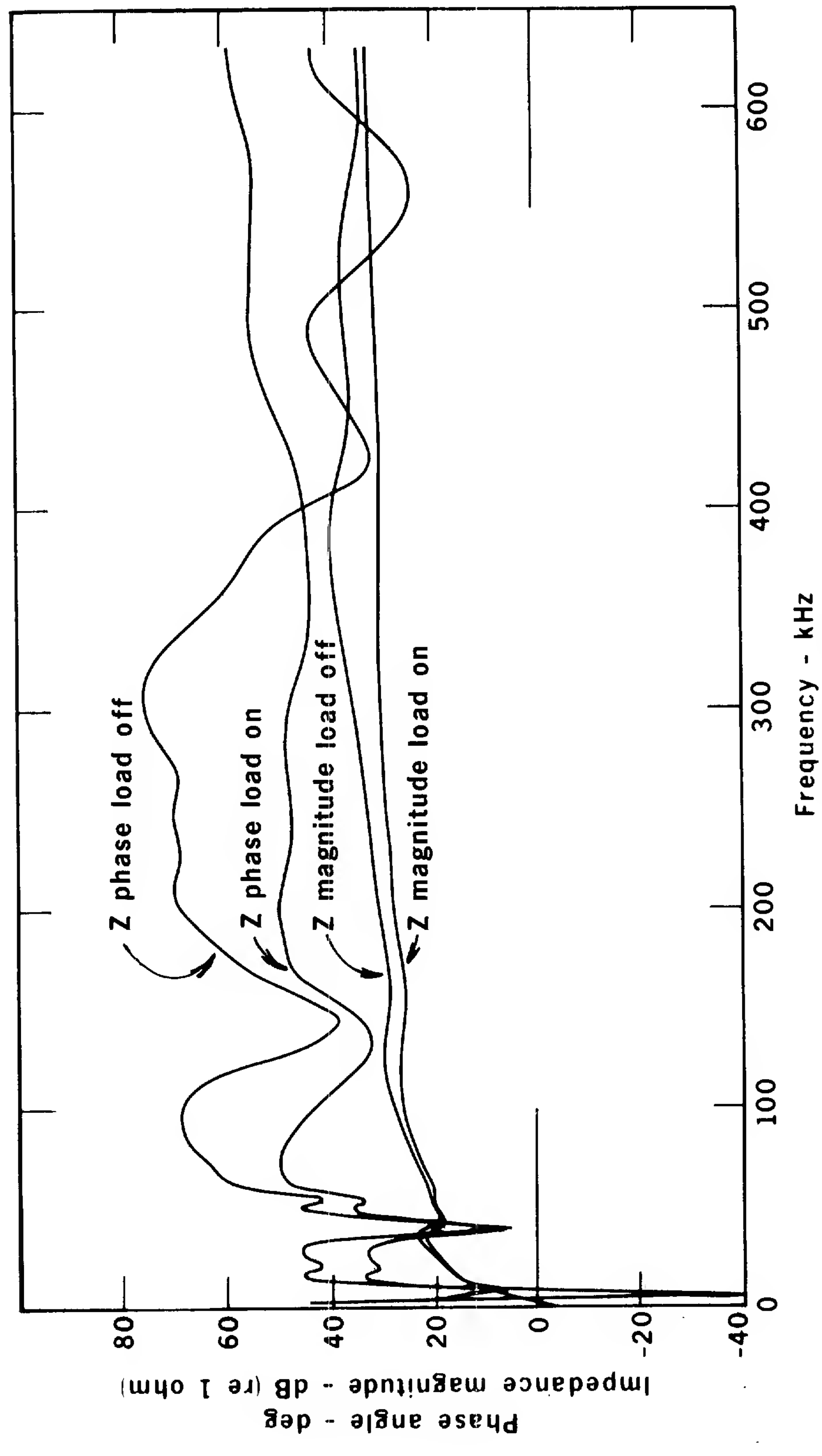

Figure 23. Location 2—Impedance, outlet 6-4; all breakers closed; load, 500 W lamps

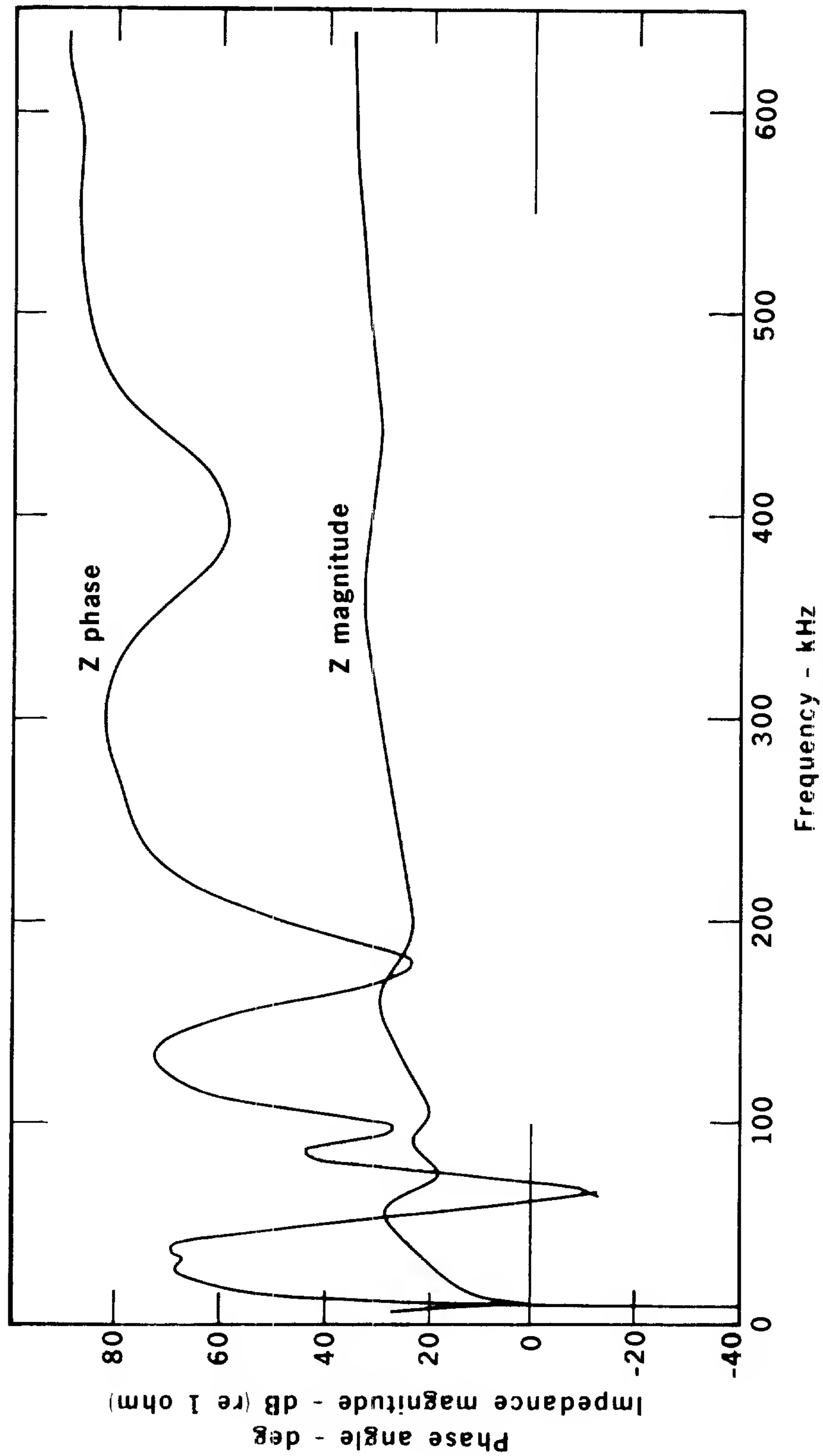

Figure 24. Location 4—Utility impedance, side A, utility measured active at breaker box; main breakers open

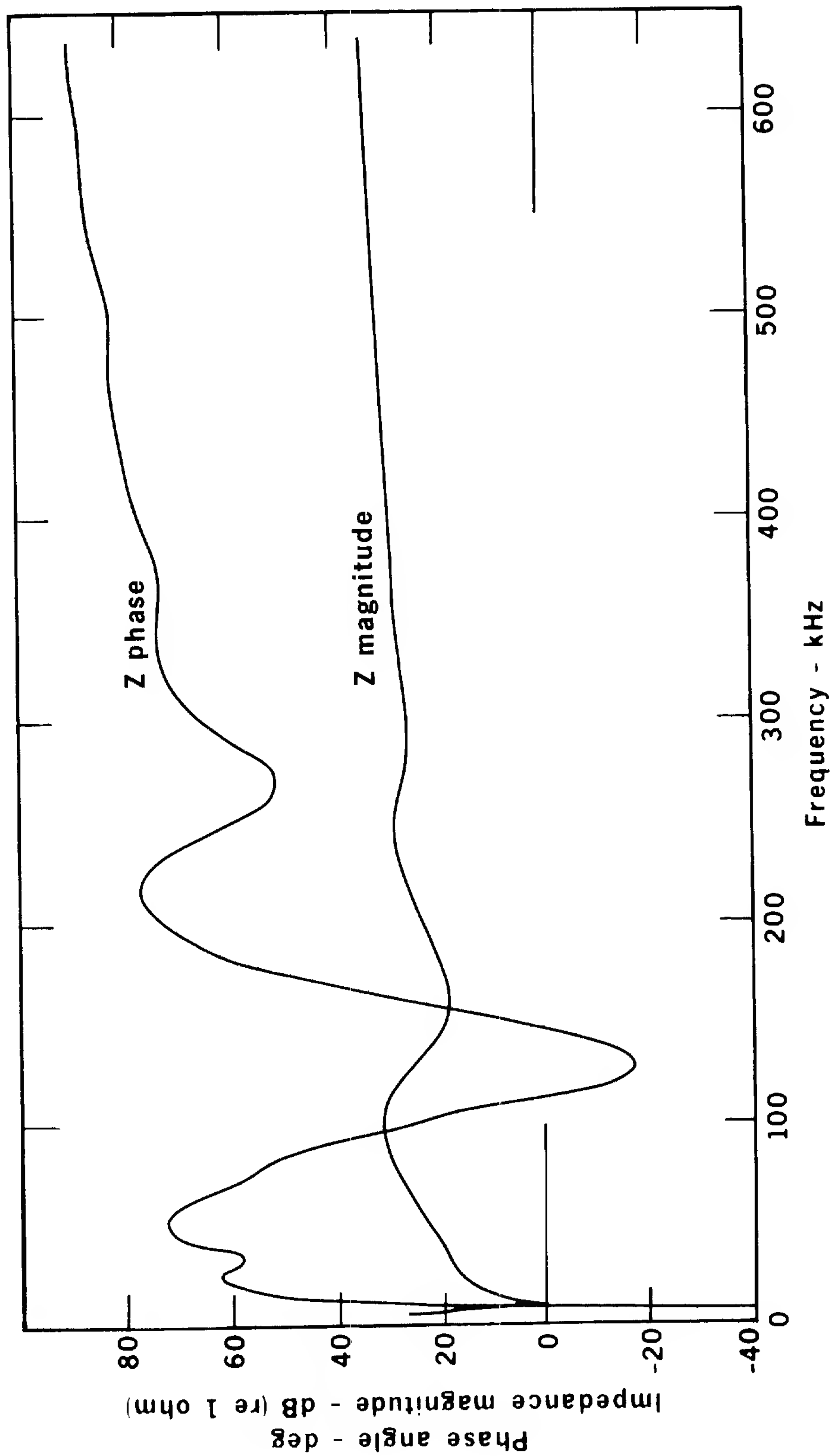

Figure 25. Location 4—Utility impedance, side B; utility measured active at breaker box; main breakers open

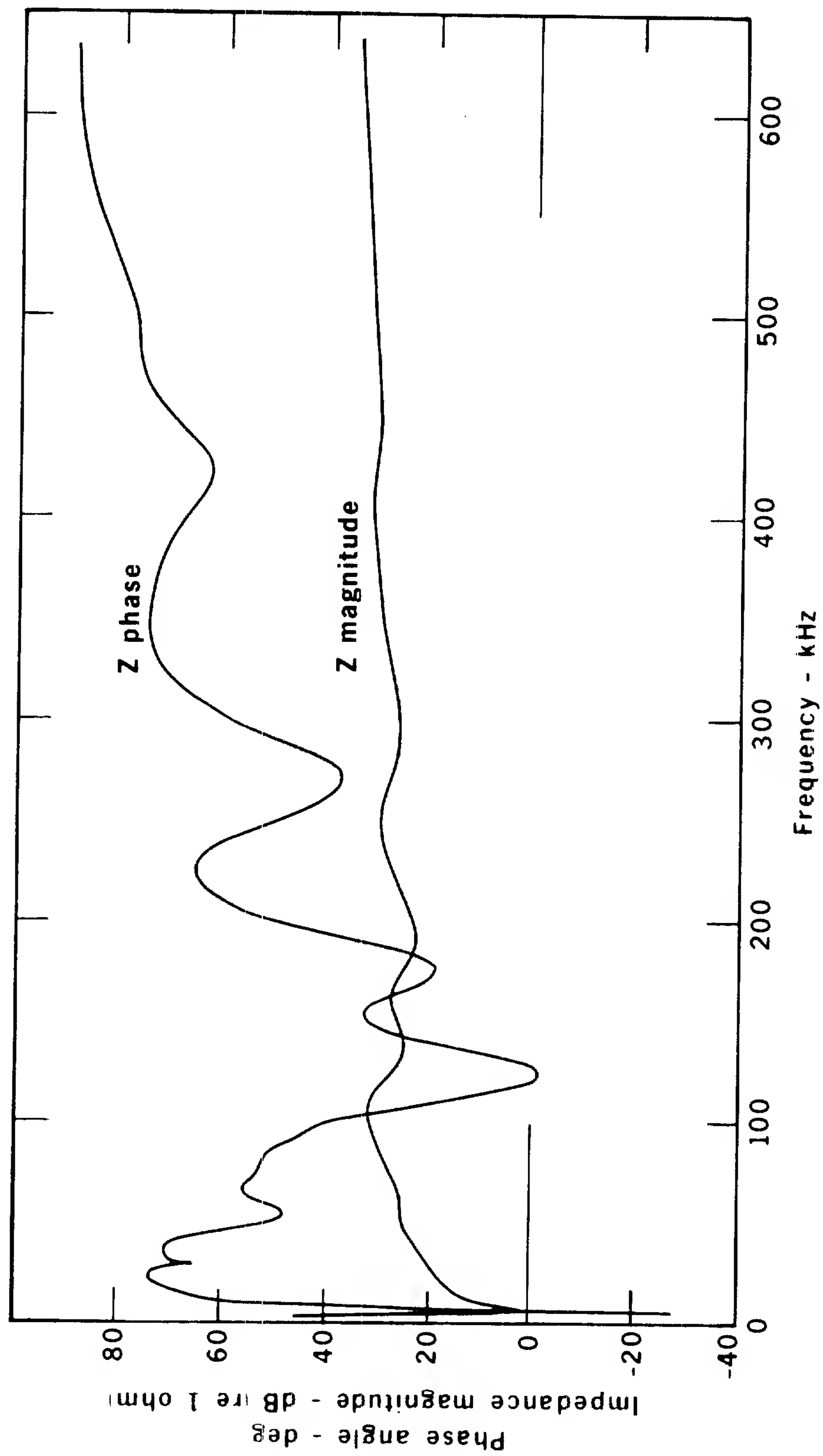

Figure 26. Location 4—Utility impedance, sides A to B; utility measured active at breaker box; main breaker open

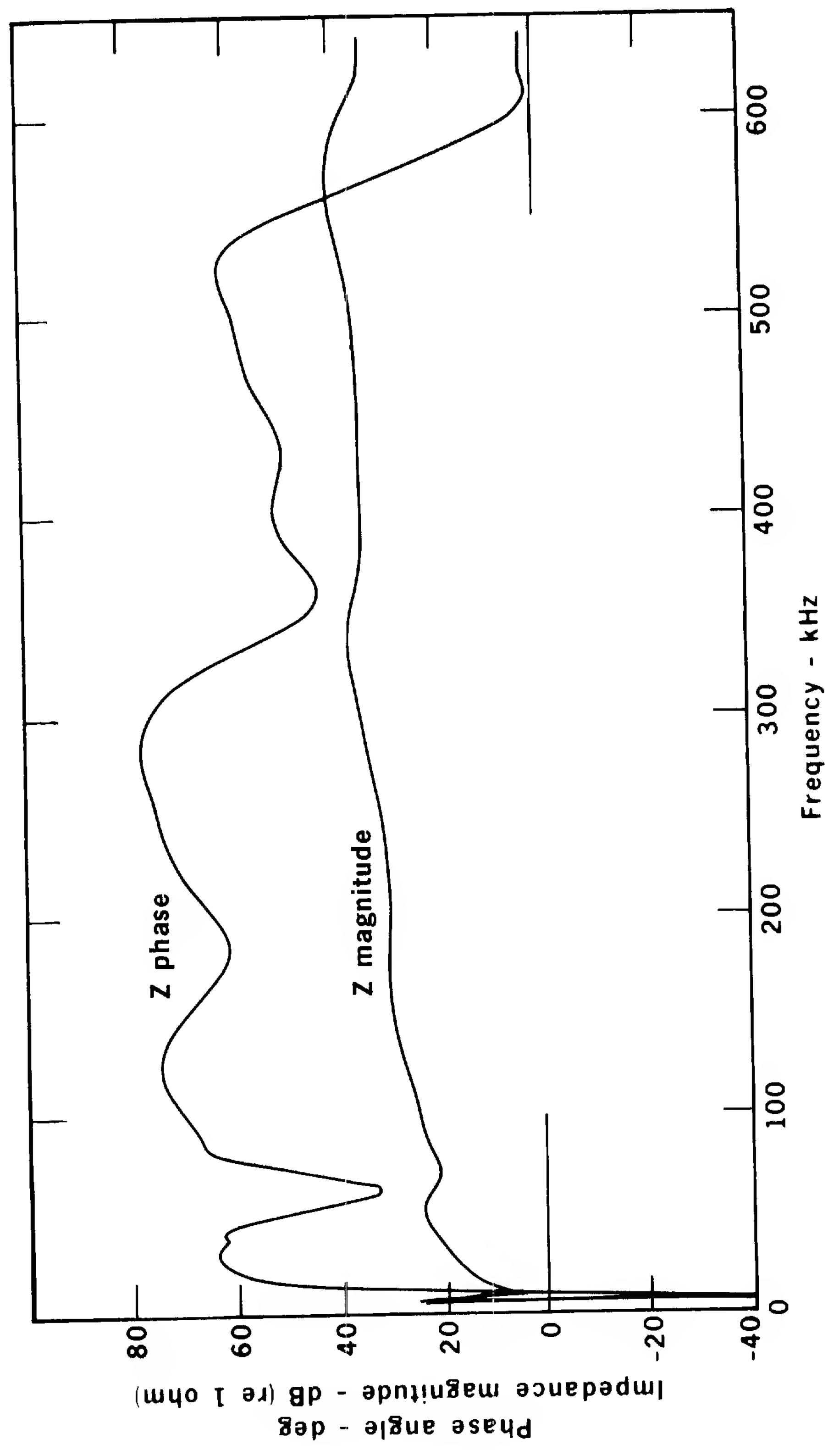

Figure 27. Location 4—Impedance, circuit-4 garage outlet, active; all breakers closed; no loads

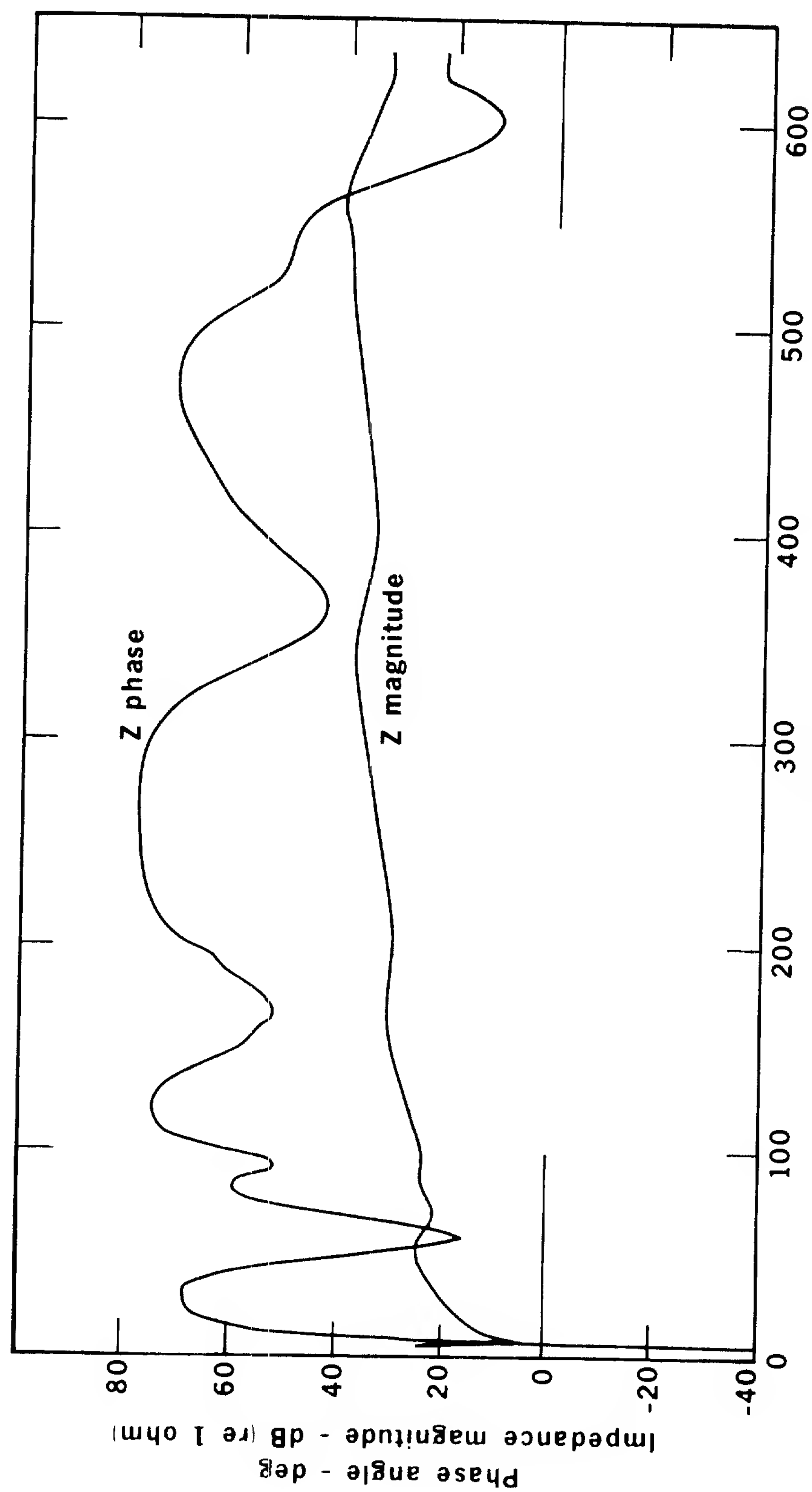

Figure 28. Location 4—Impedance, washing machine outlet circuit 4, active; all breakers closed; no loads

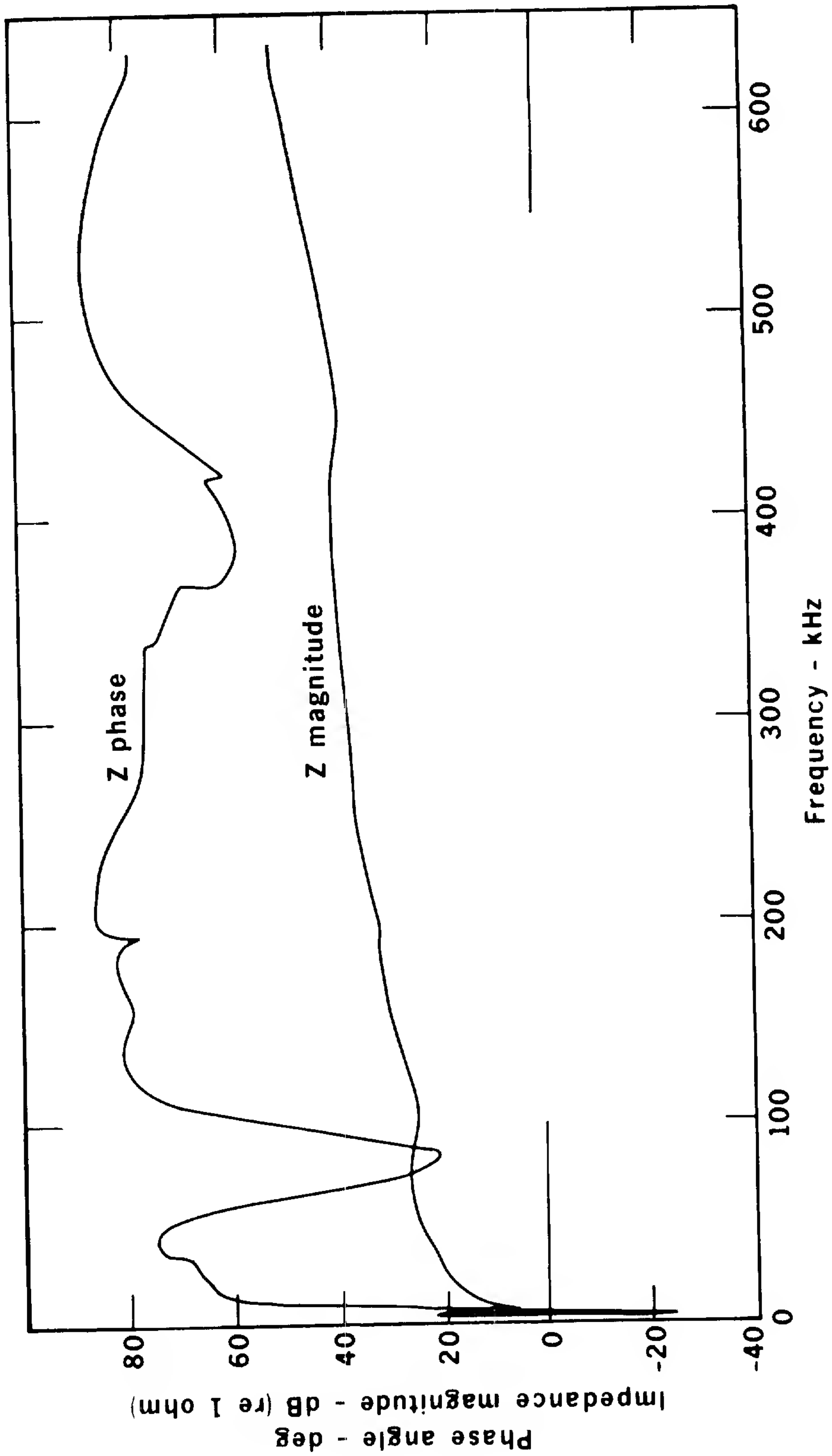

Figure 29. Location 4—Impedance, garage ceiling outlet, active; all breakers closed; no loads

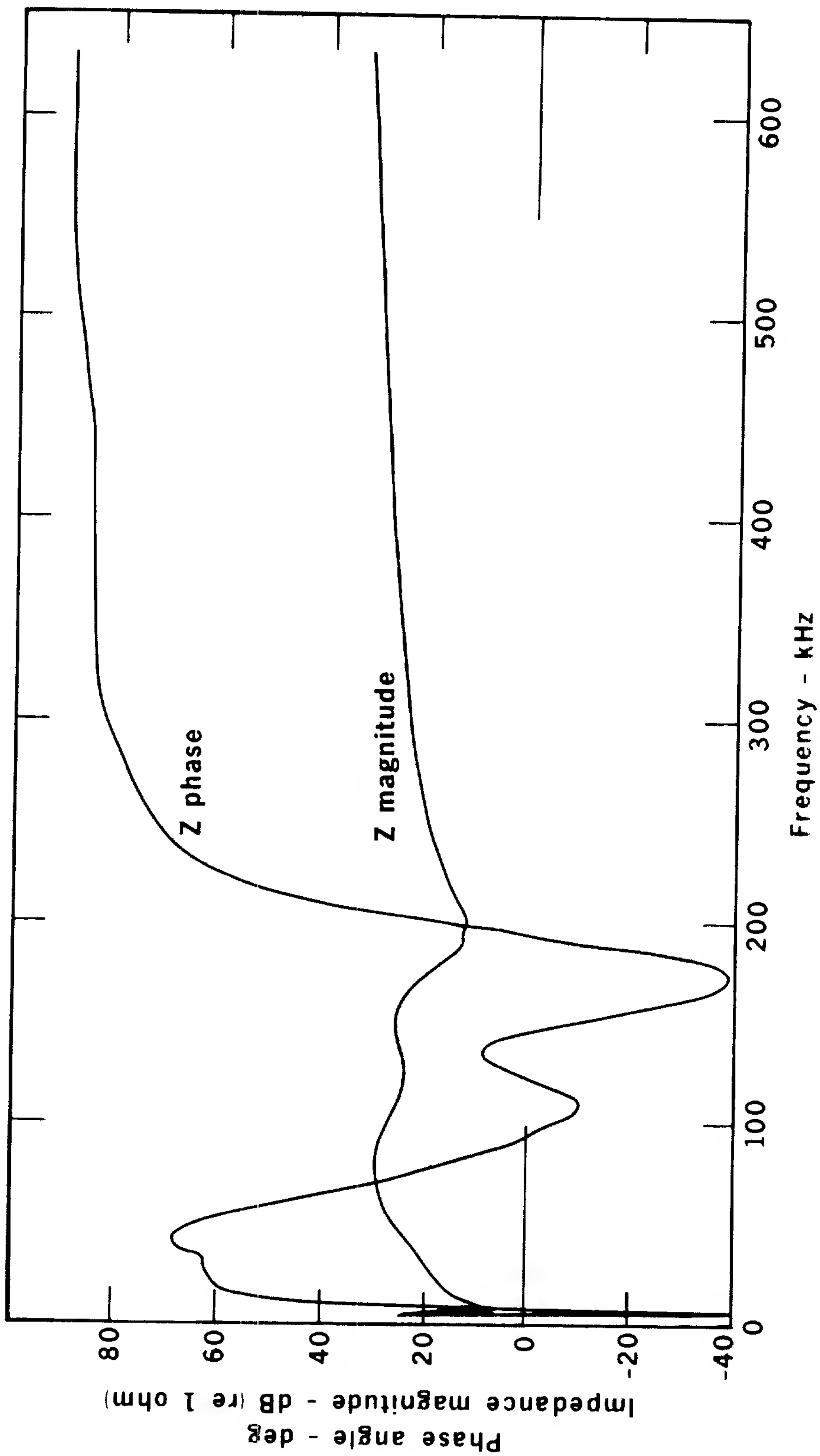

Figure 30. Location 4—Impedance, refrigerator outlet circuit 6, active; all breakers closed; no loads

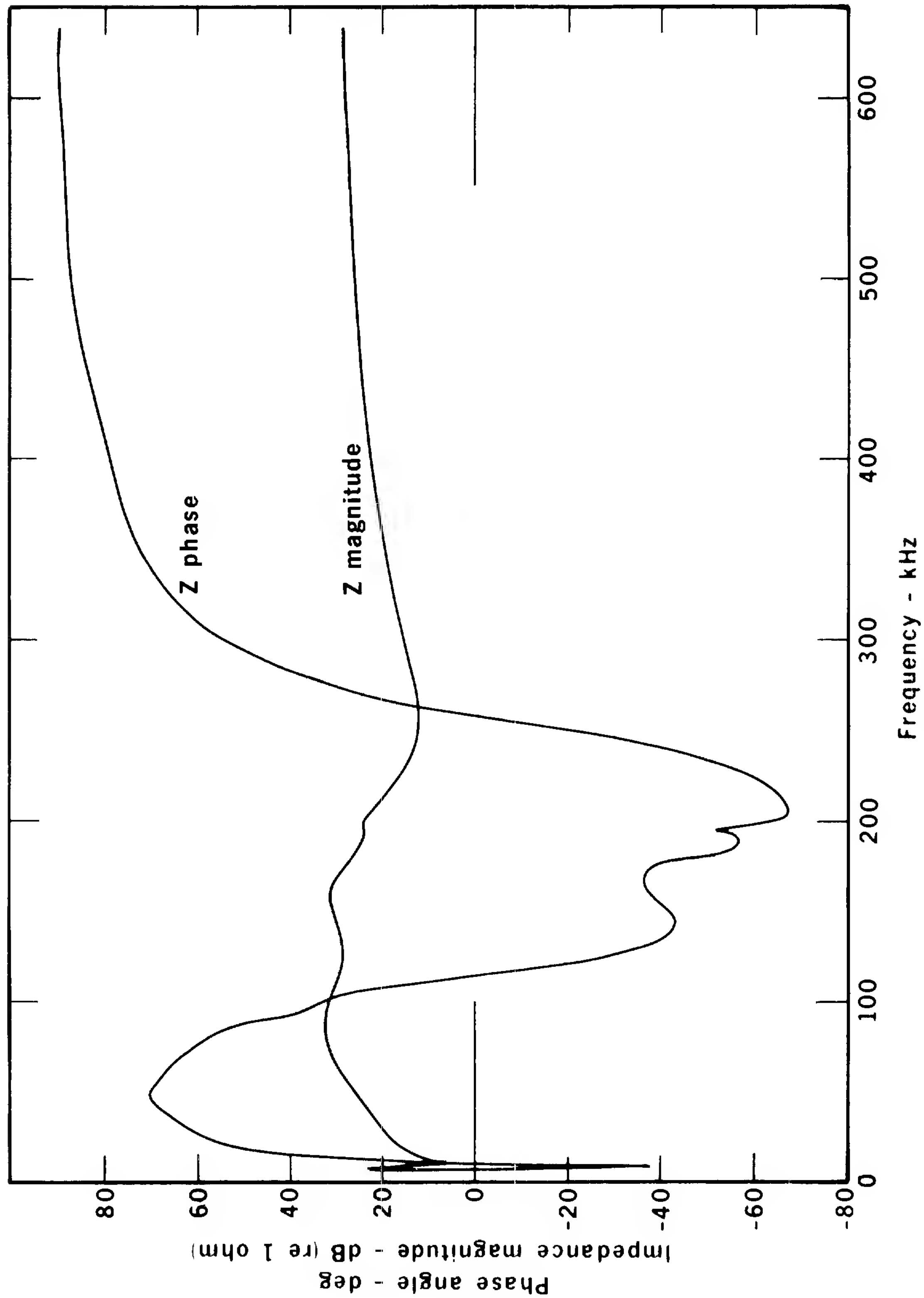

Figure 31. Location 4—Impedance, freezer outlet circuit 6, active; all breakers closed; no loads

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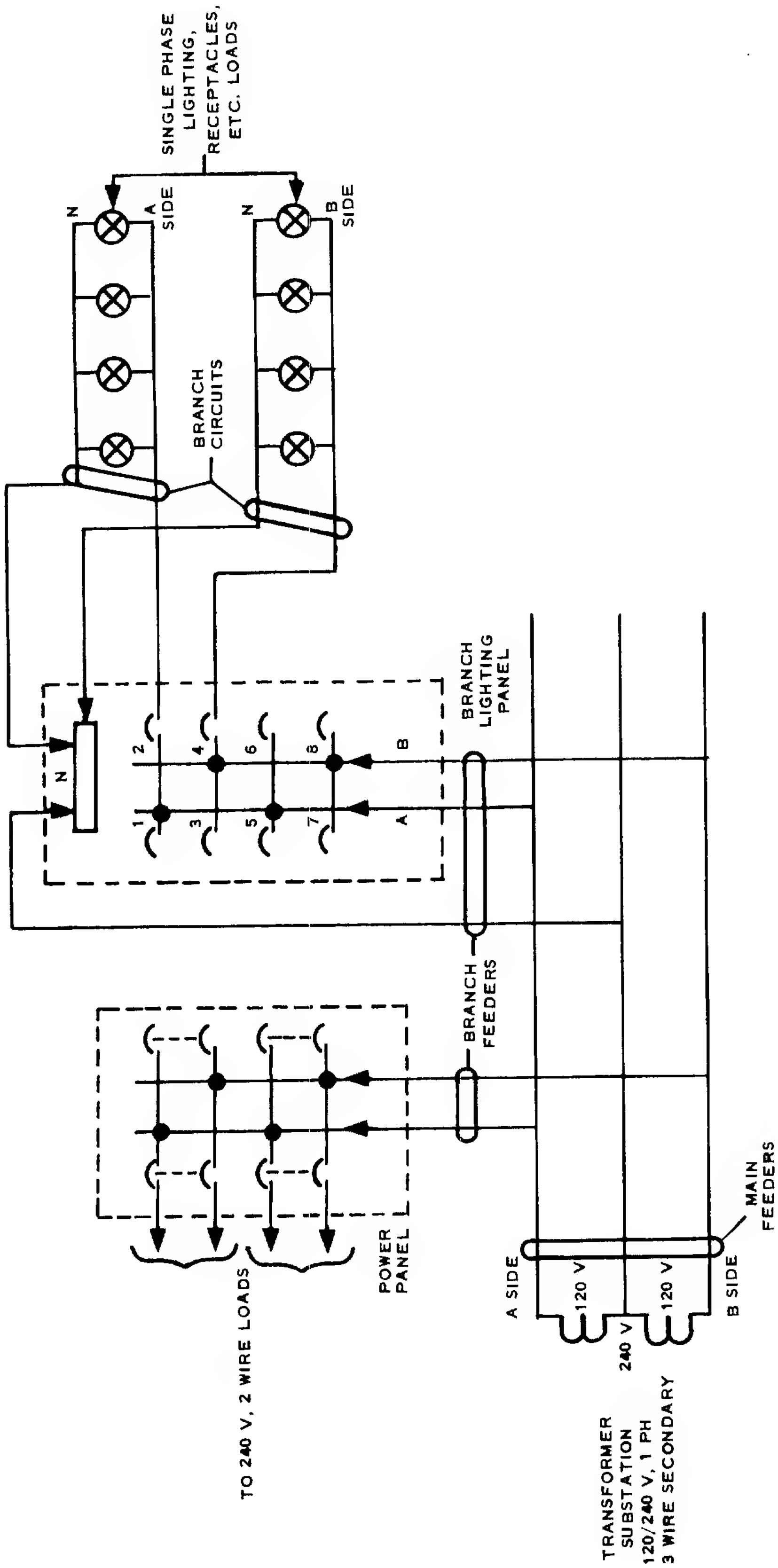

Figure 32. Typical single-phase, 3-wire, 120/240 V secondary distribution system

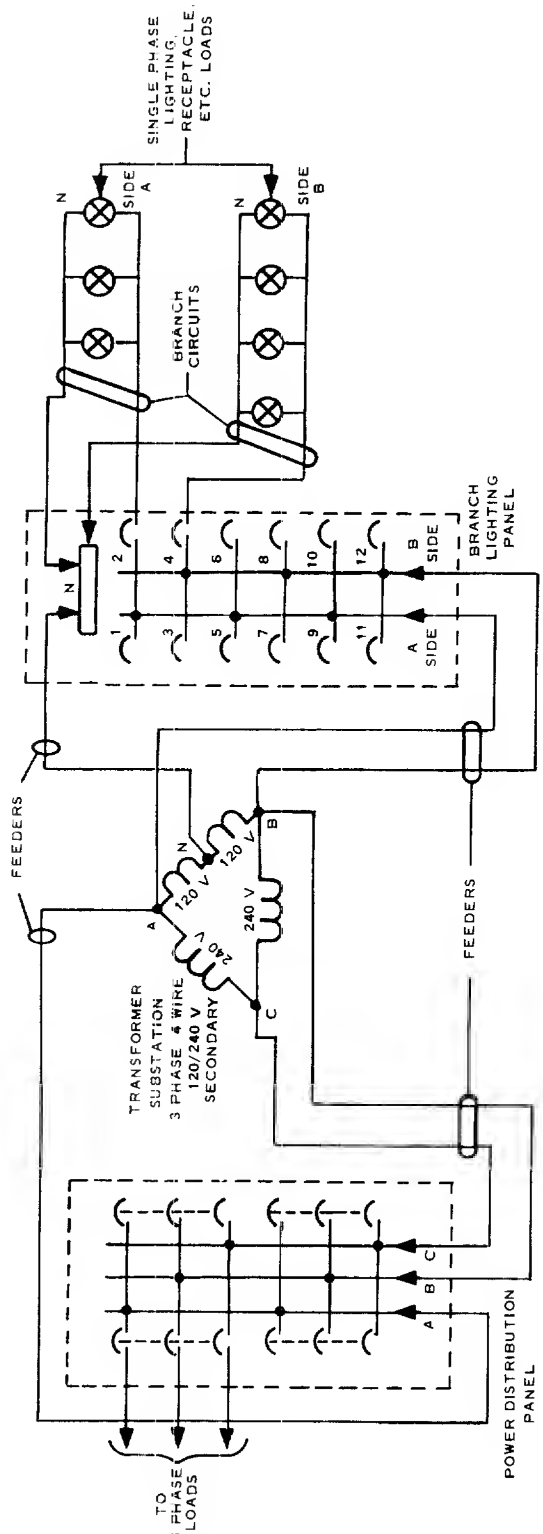

Figure 33. Typical 3-phase, 4-wire, center-tap secondary distribution system

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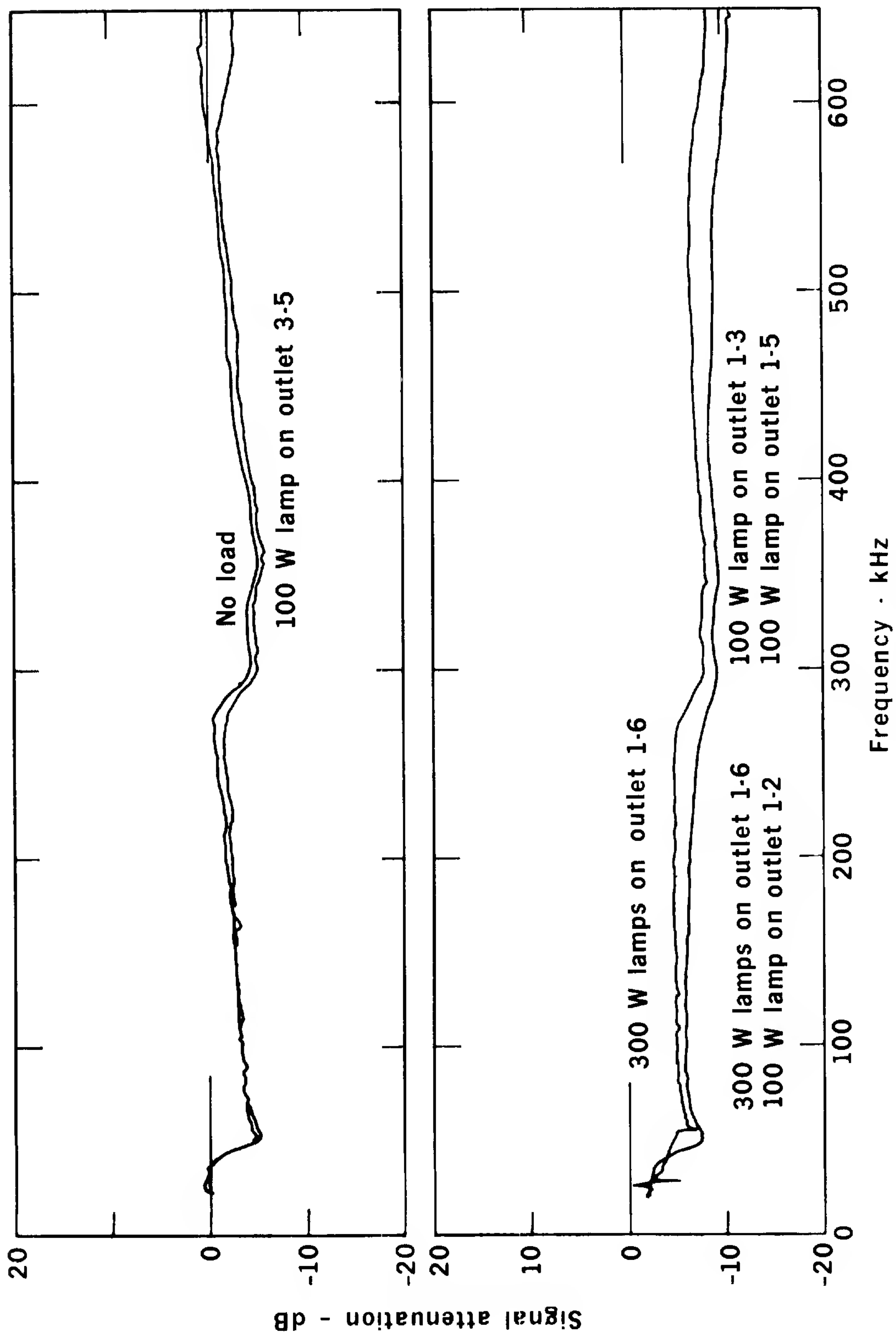

Figure 36. Location 1—Signal attenuation; same branch circuit outlets 1-4 to 1-8 (side B)

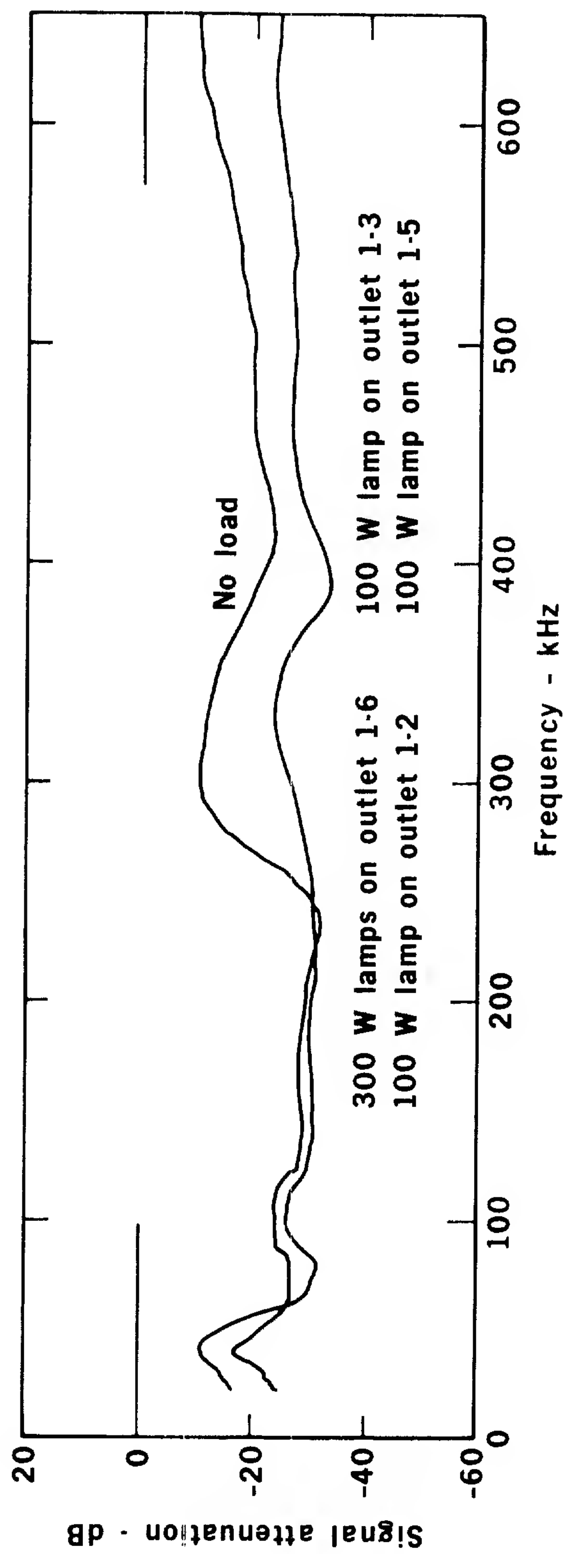

Figure 37. Location 1—Signal attenuation, outlets 1-4 to 4-6 (B side to A side)

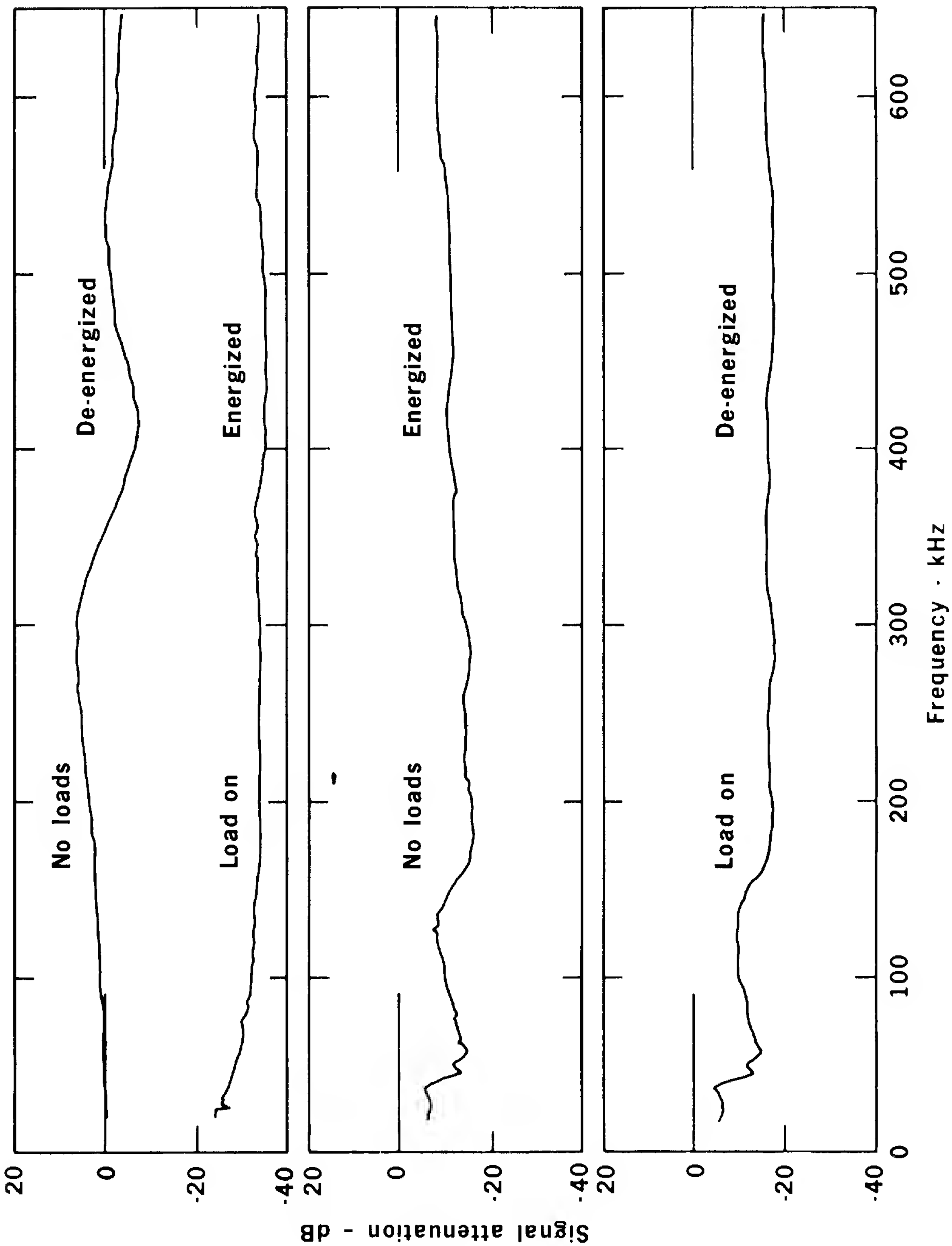

Figure 38. Location 2—Signal attenuation, outlets 4-6 to 10-5 (B side); load is a 200 W lamp at outlet 10-5; all measurements are high to neutral

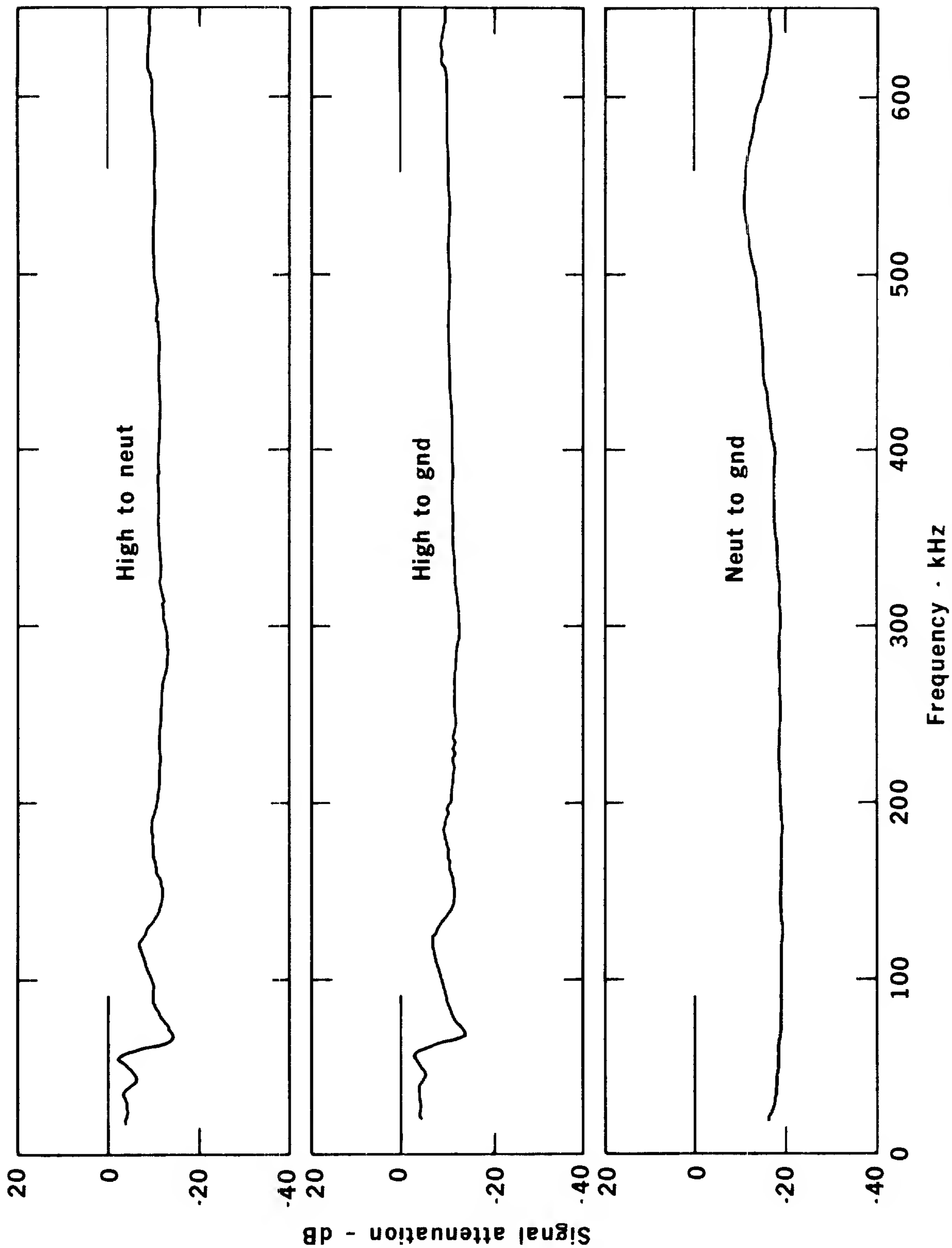

Figure 39. Location 2—Signal attenuation, circuit 9 to circuit 3 (A side); energized with no loads

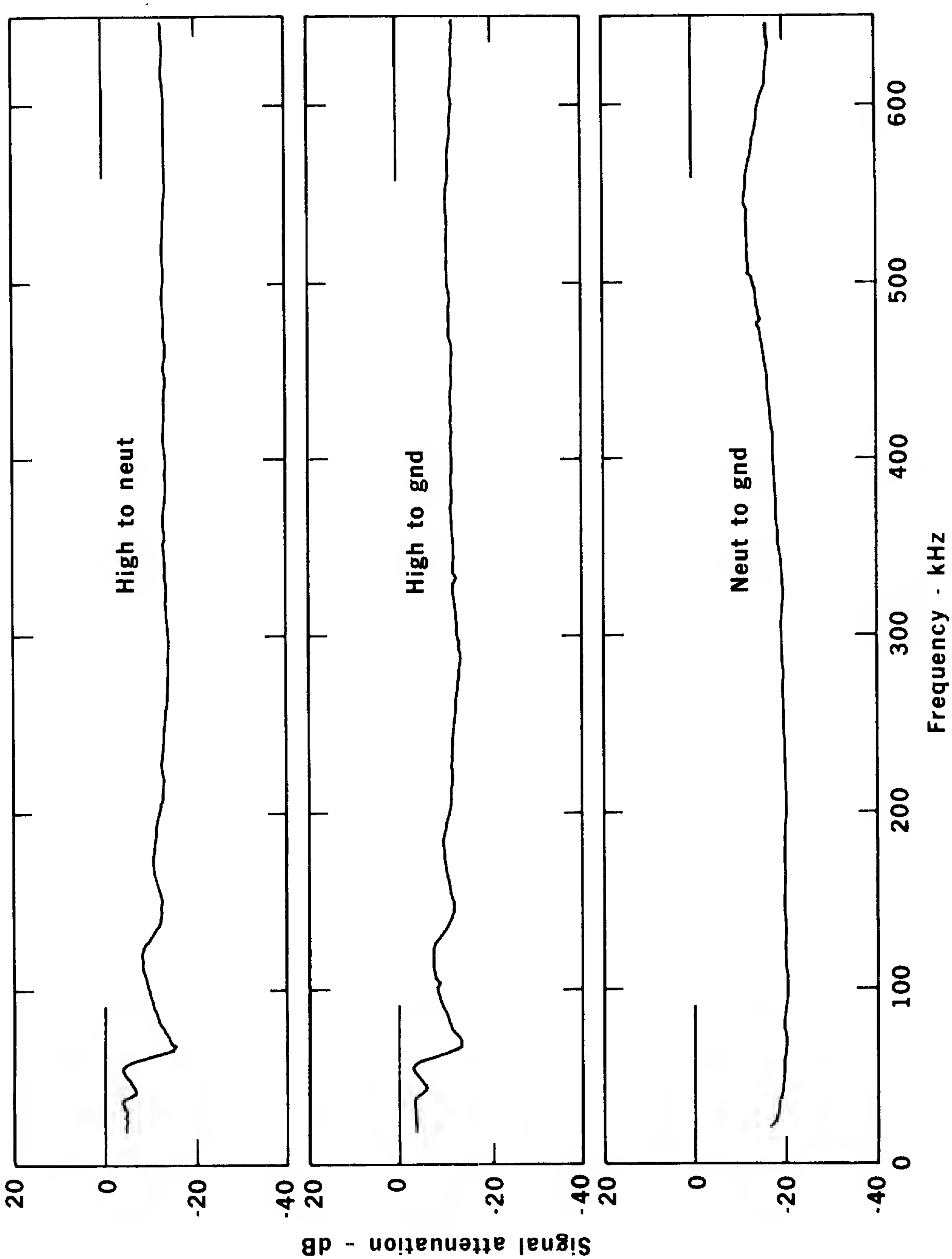

Figure 40. Location 2—Signal attenuation, circuit 9 to circuit 3 (A side); energized with a 200 W lamp at outlet 3-3

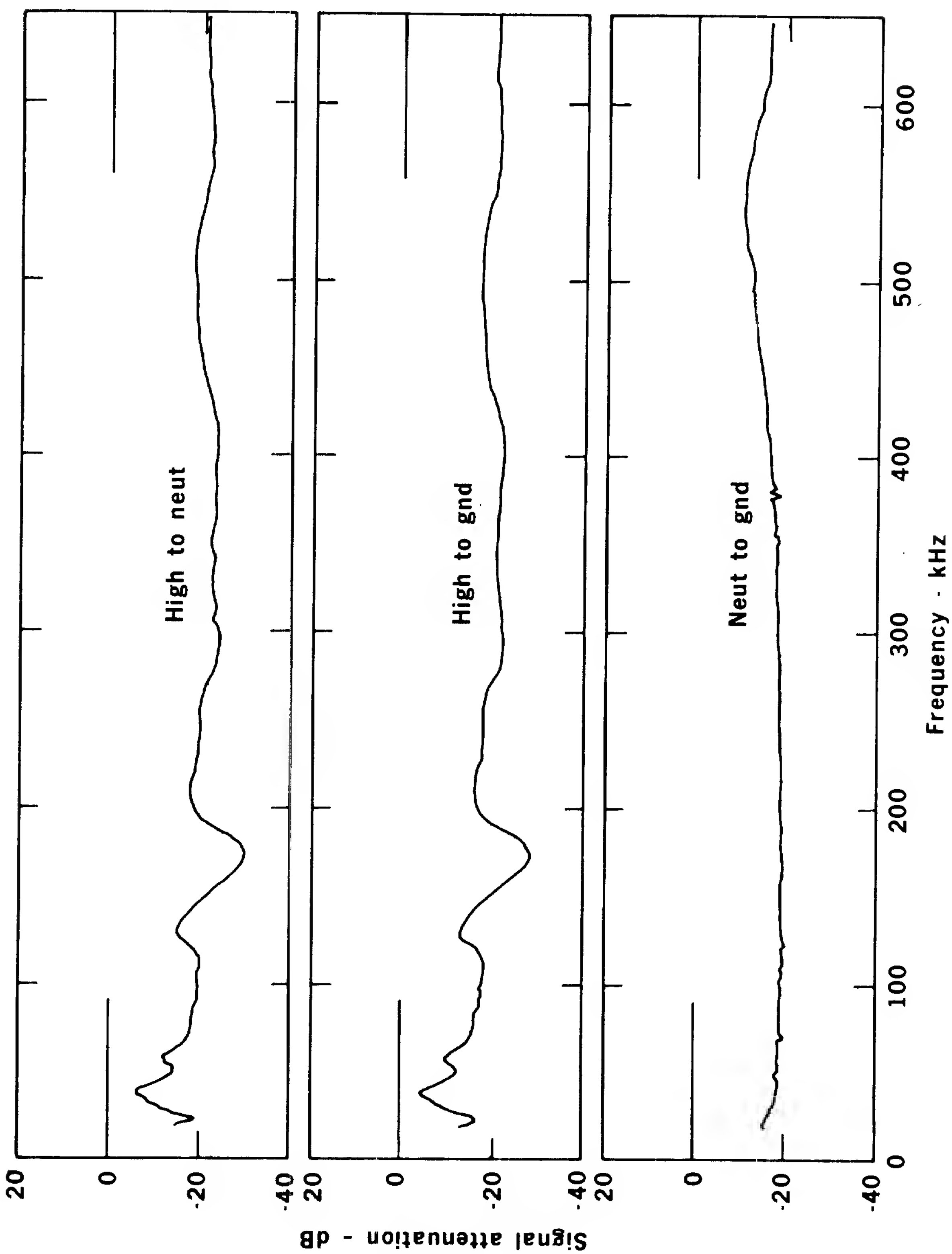

Figure 41. Location 2—Signal attenuation, circuit 9 to circuit 8 (side A to side B); energized with no loads

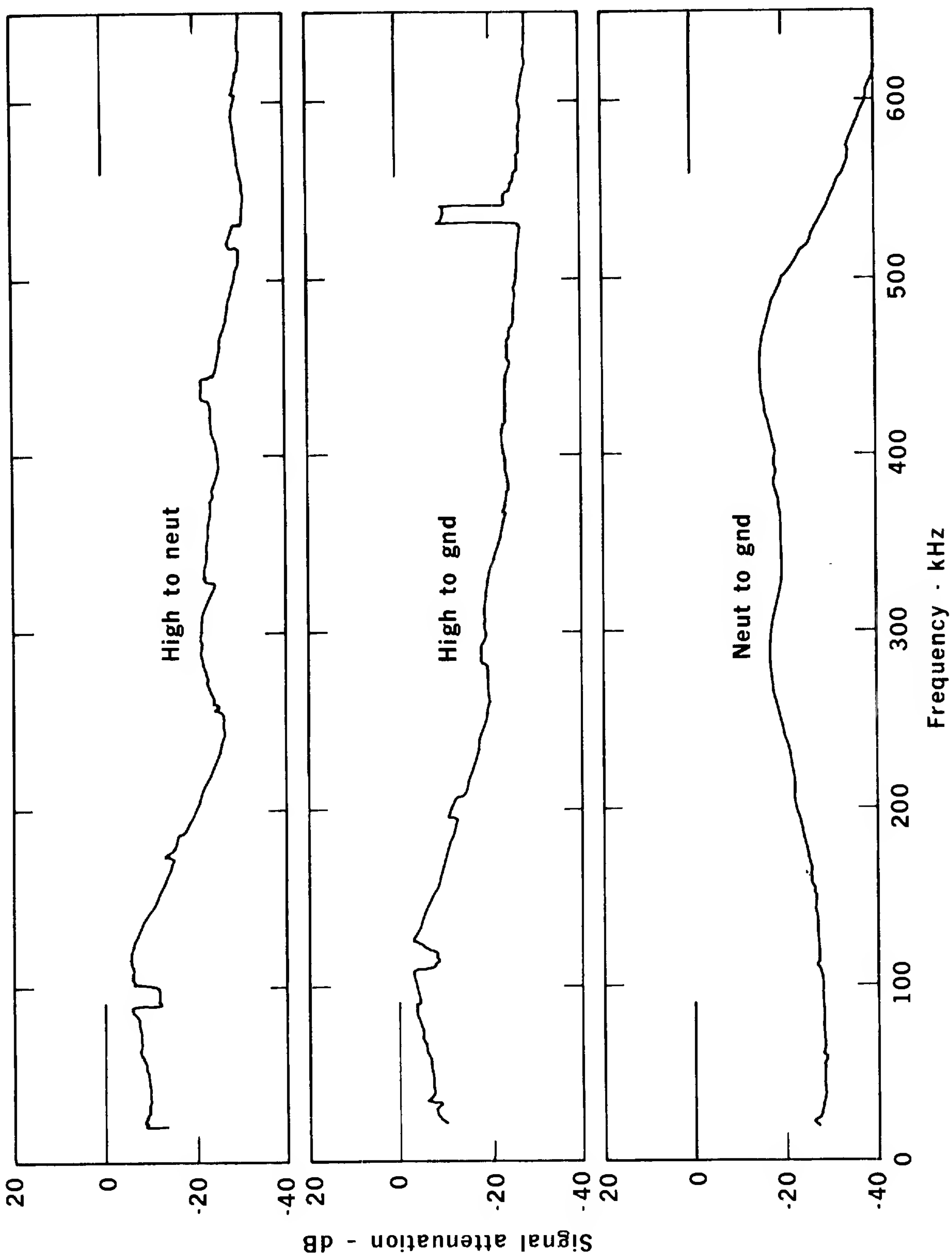

Figure 42. Location 3—Signal attenuation, floor 10, outlets B-14B to B-28 (black phase); energized with unknown loads

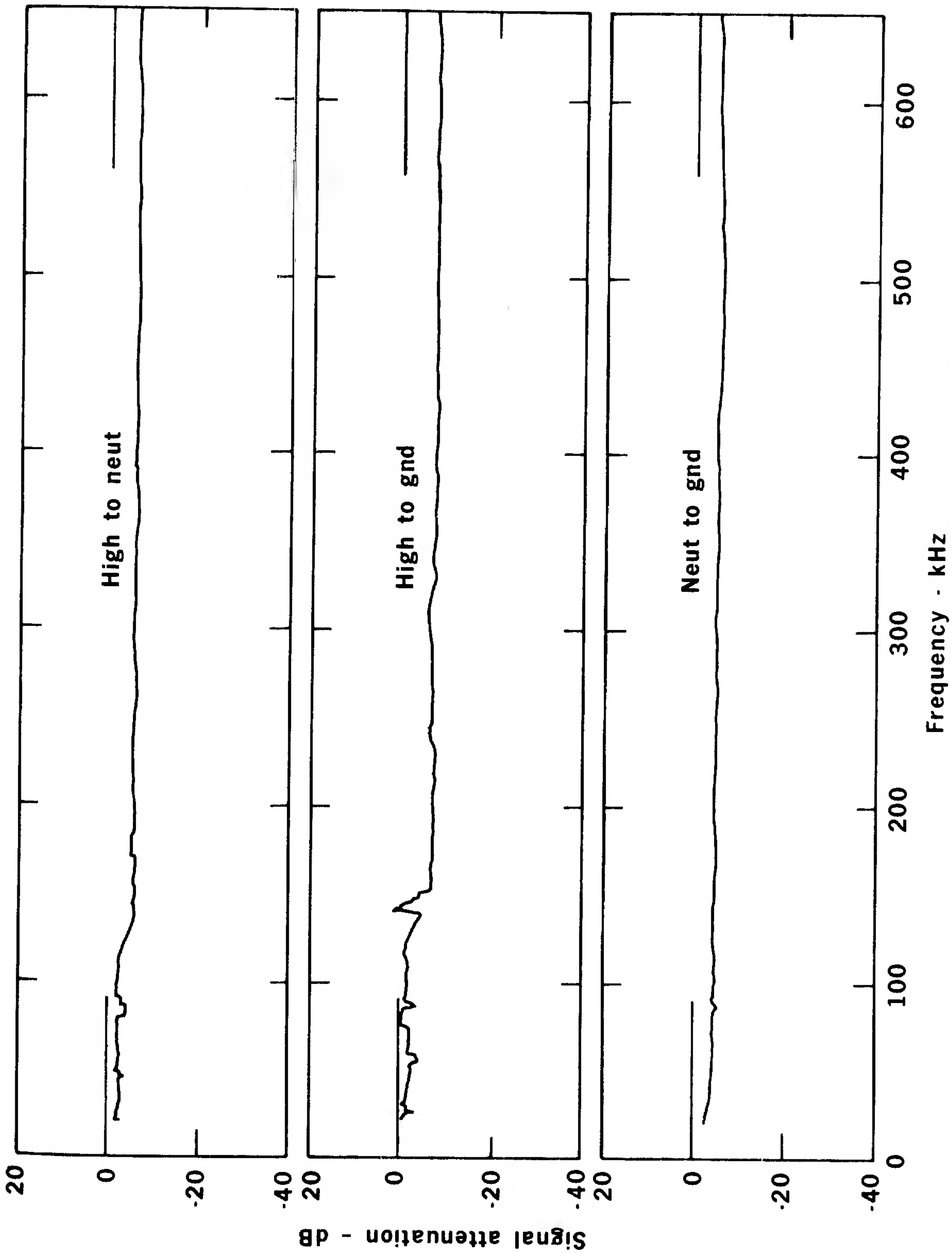

Figure 43. Location 3—Signal attenuation, floor 10, outlets B-14A to B-14B (black phase); energized with unknown loads

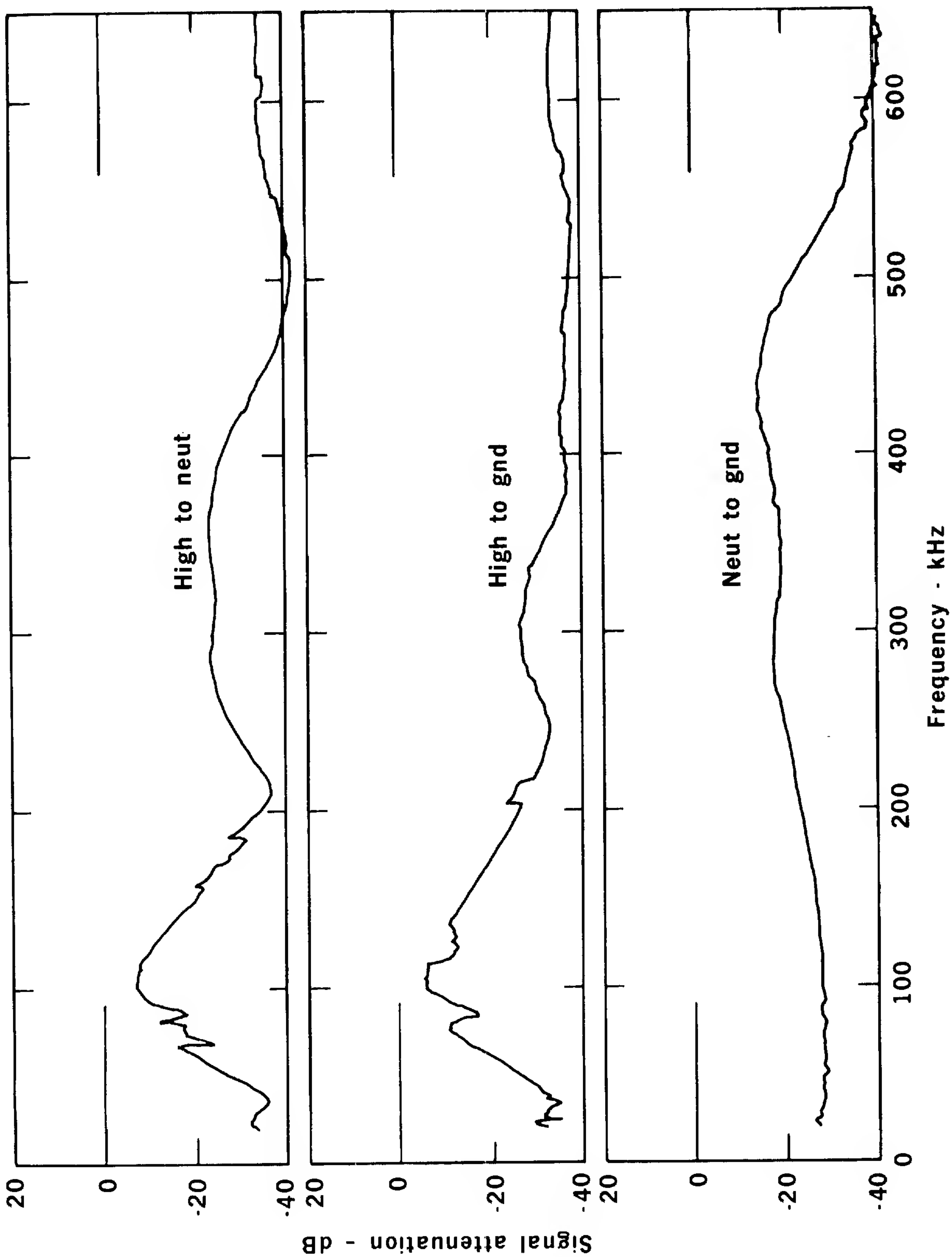

Figure 44. Location 3—Signal attenuation, floor 10, outlets B-14B to B-4 (black to red phases); energized with unknown loads

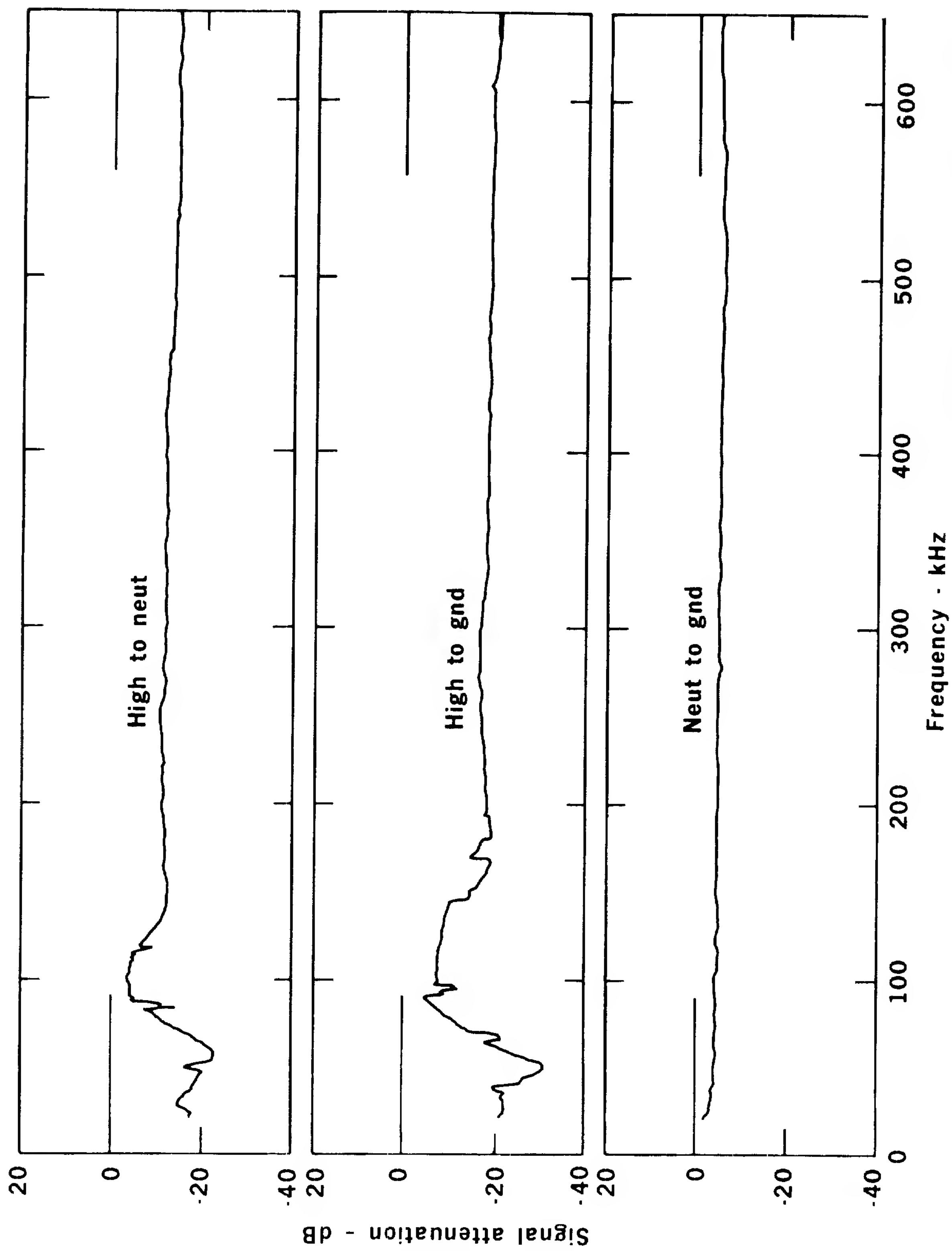

Figure 45. Location 3—Signal attenuation, floor 10, outlets B-14A to B-16 (black to red phases); energized with unknown loads

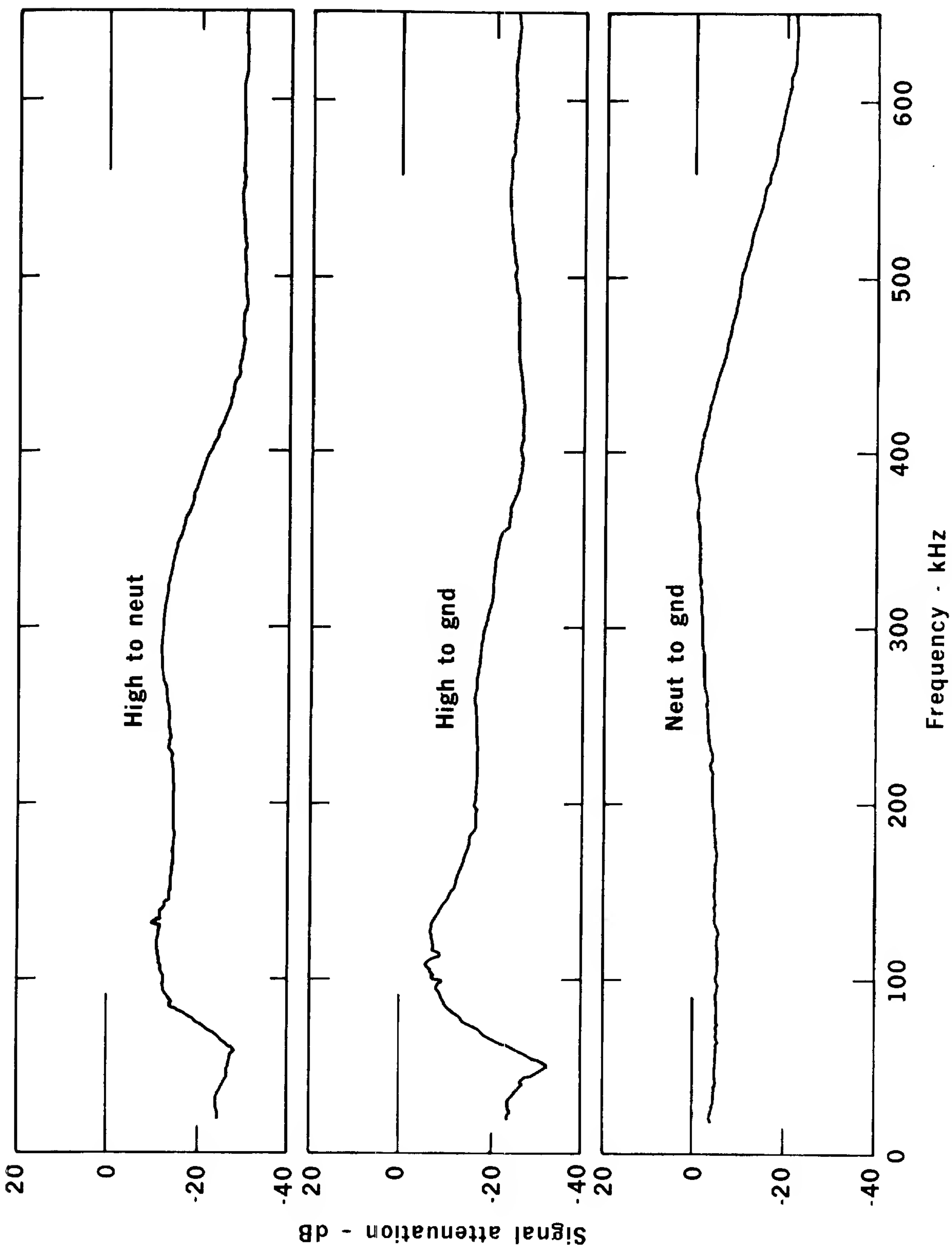

Figure 46. Location 3—Signal attenuation, floor 10, outlets B-18 to B-16 (blue to red phases); energized with unknown loads

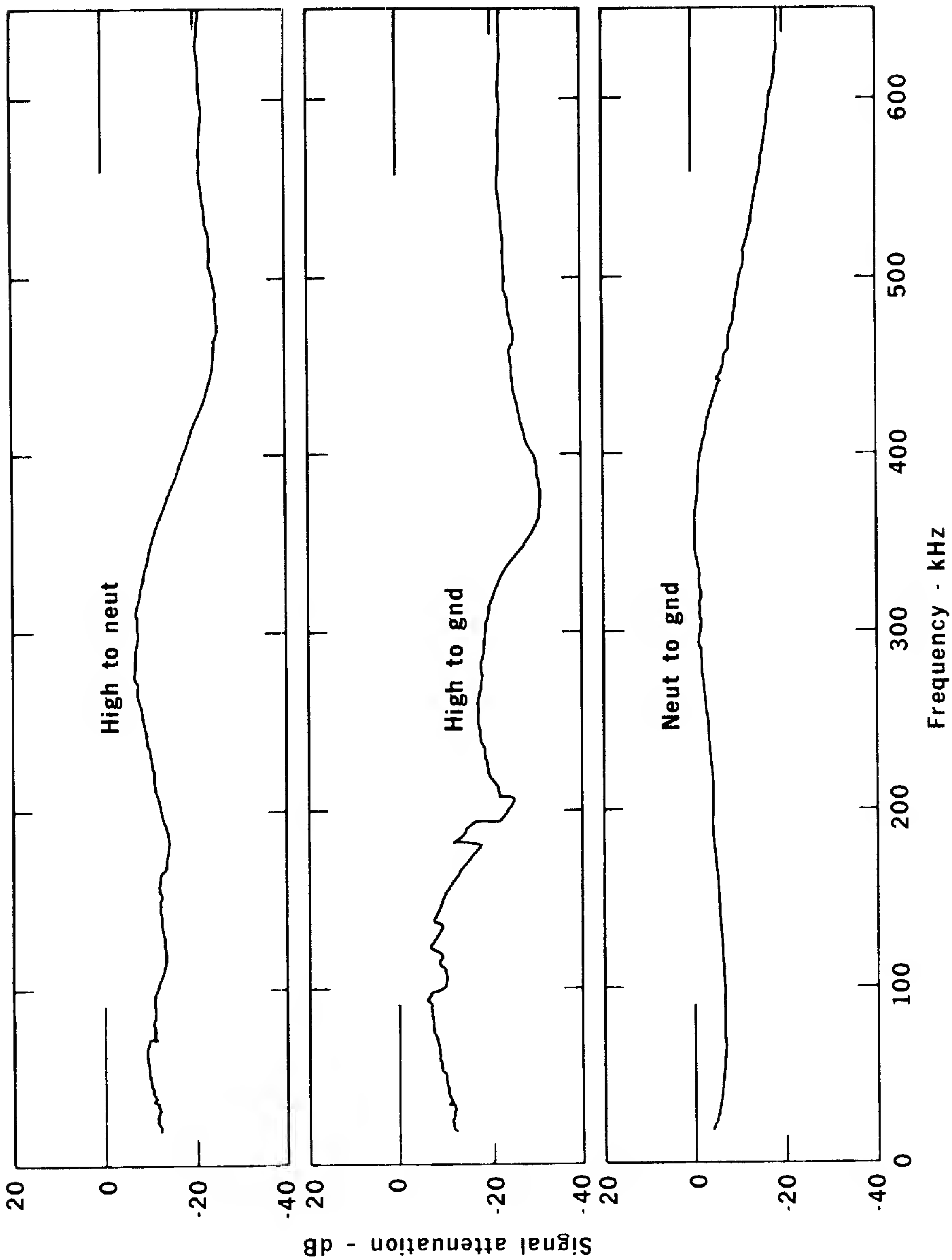

Figure 47. Location 3—Signal attenuation, floor 10, outlets B-18 to B-148 (black to blue phases); energized with unknown loads

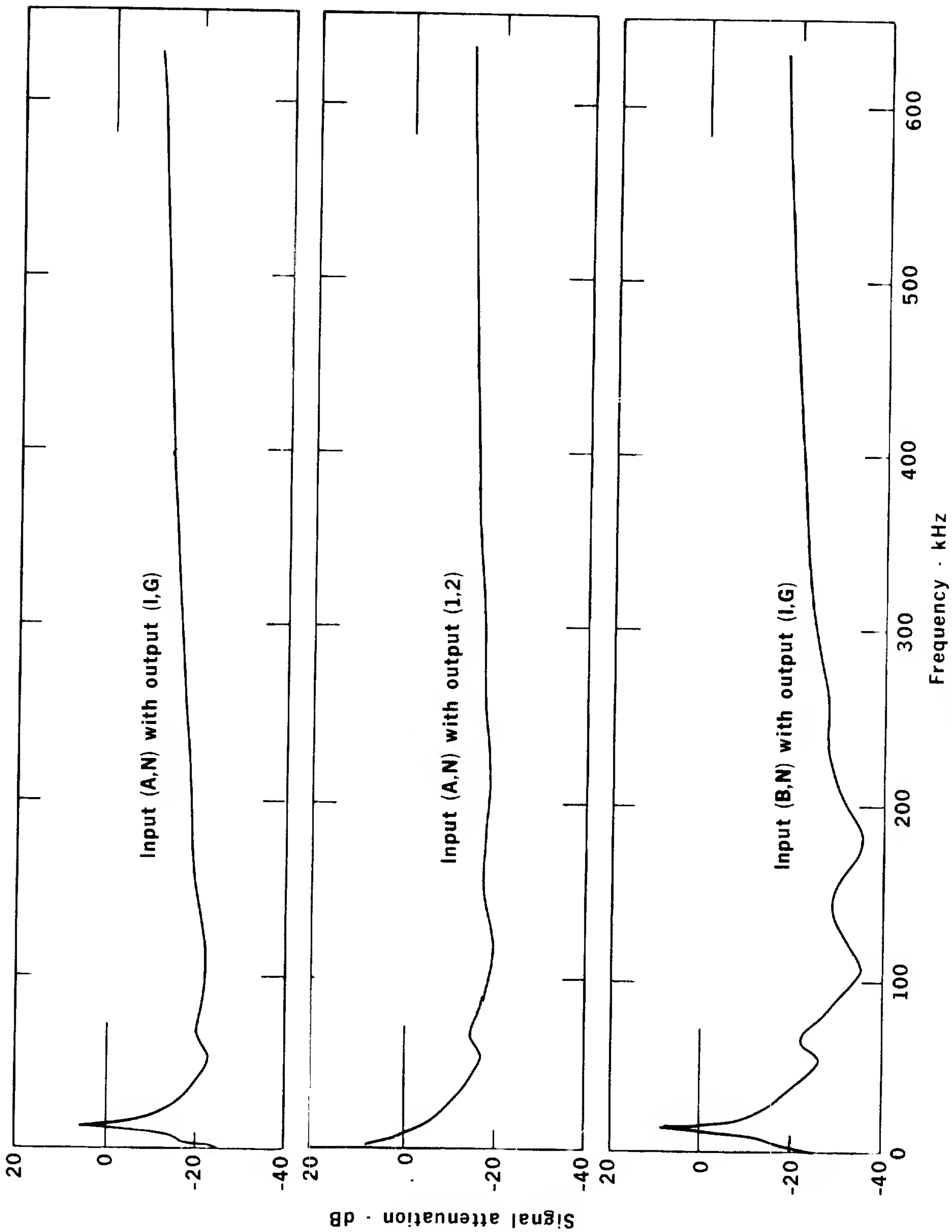

Figure 48. Transformer signal attenuation—low to high side

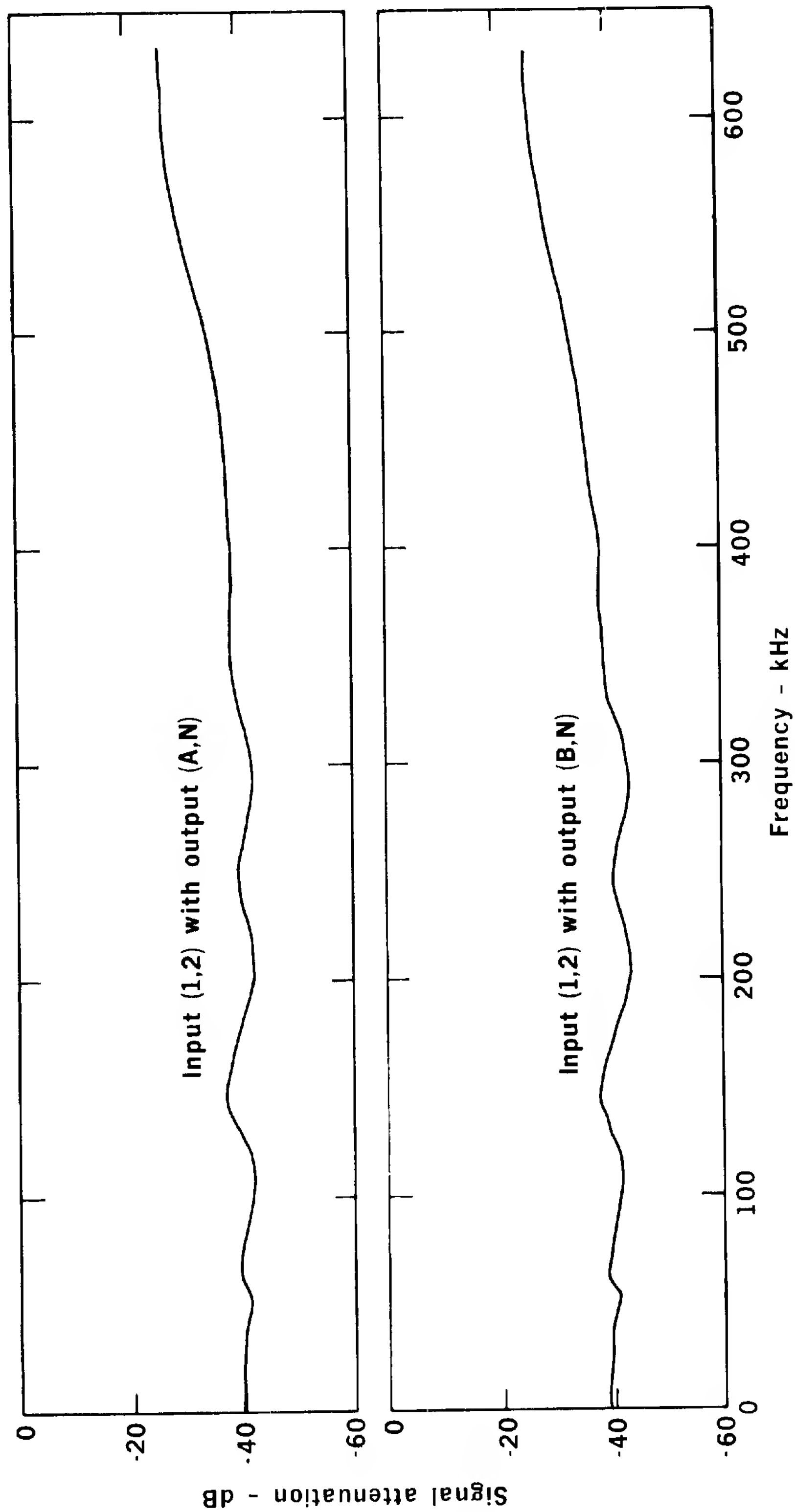

Figure 49. Transformer signal attenuation—high to low side

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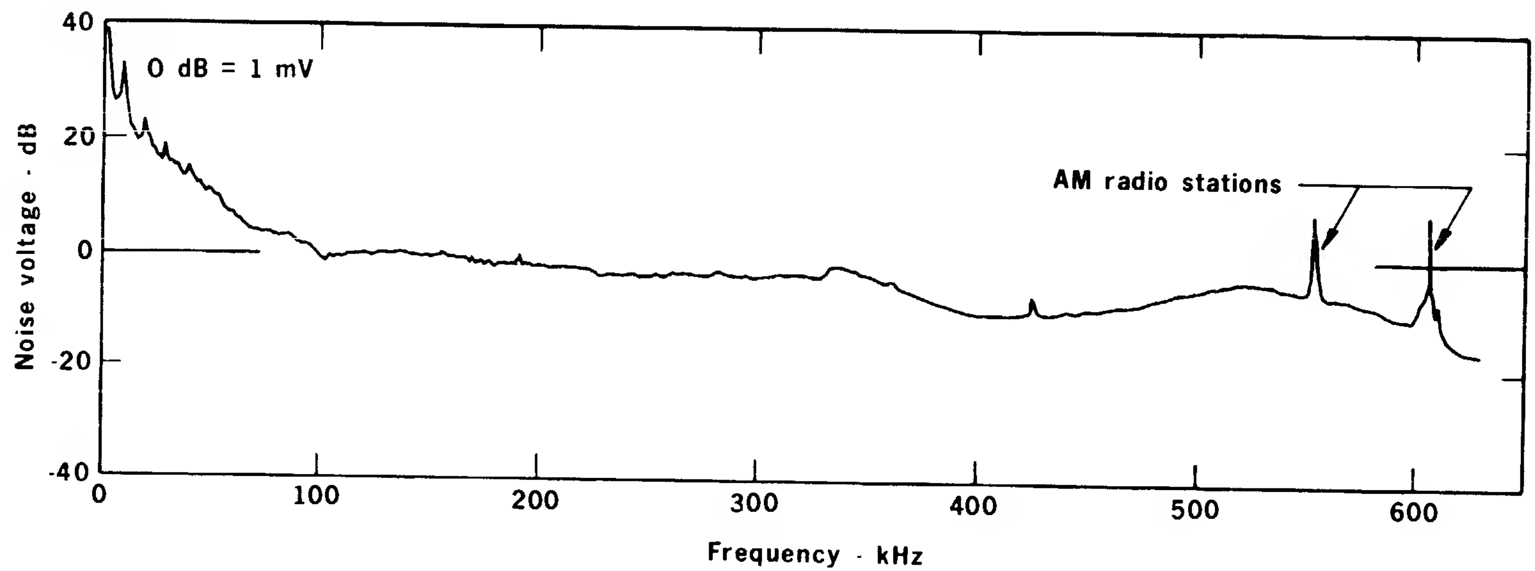

Figure 50. Noise of universal motor—1/2-in. power drill measured active at location 4

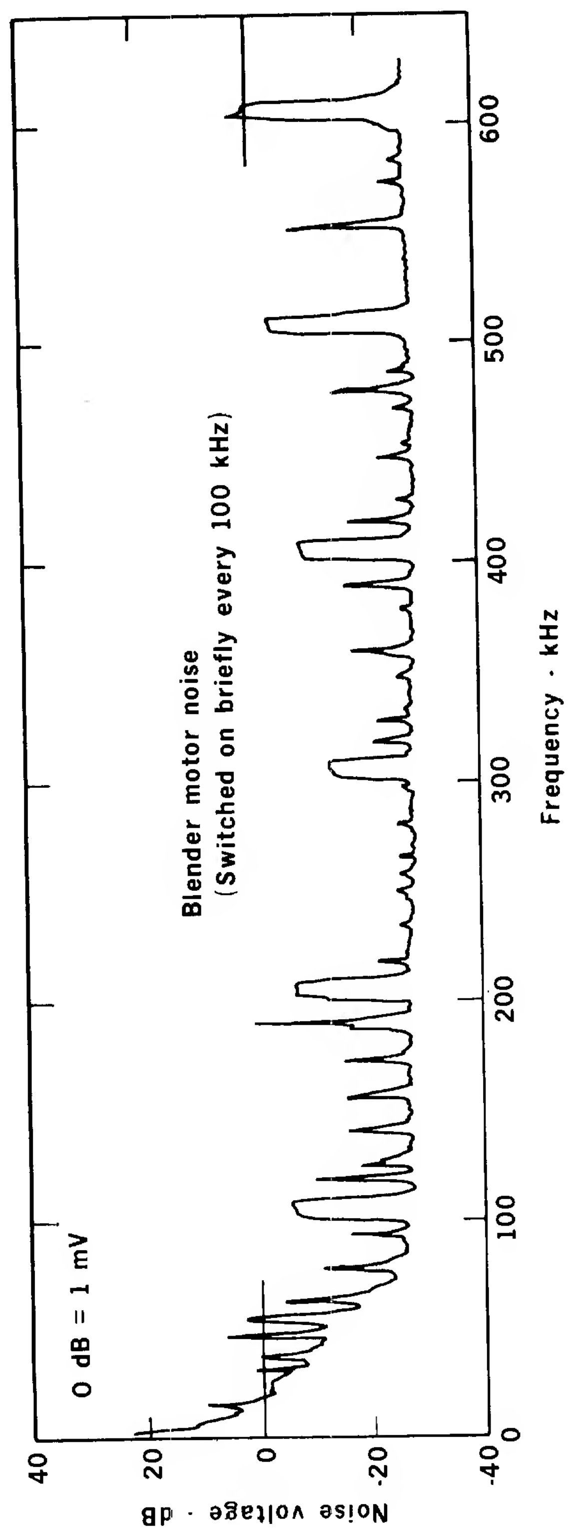

Figure 51. Noise of universal motor (blender) taken at location 1

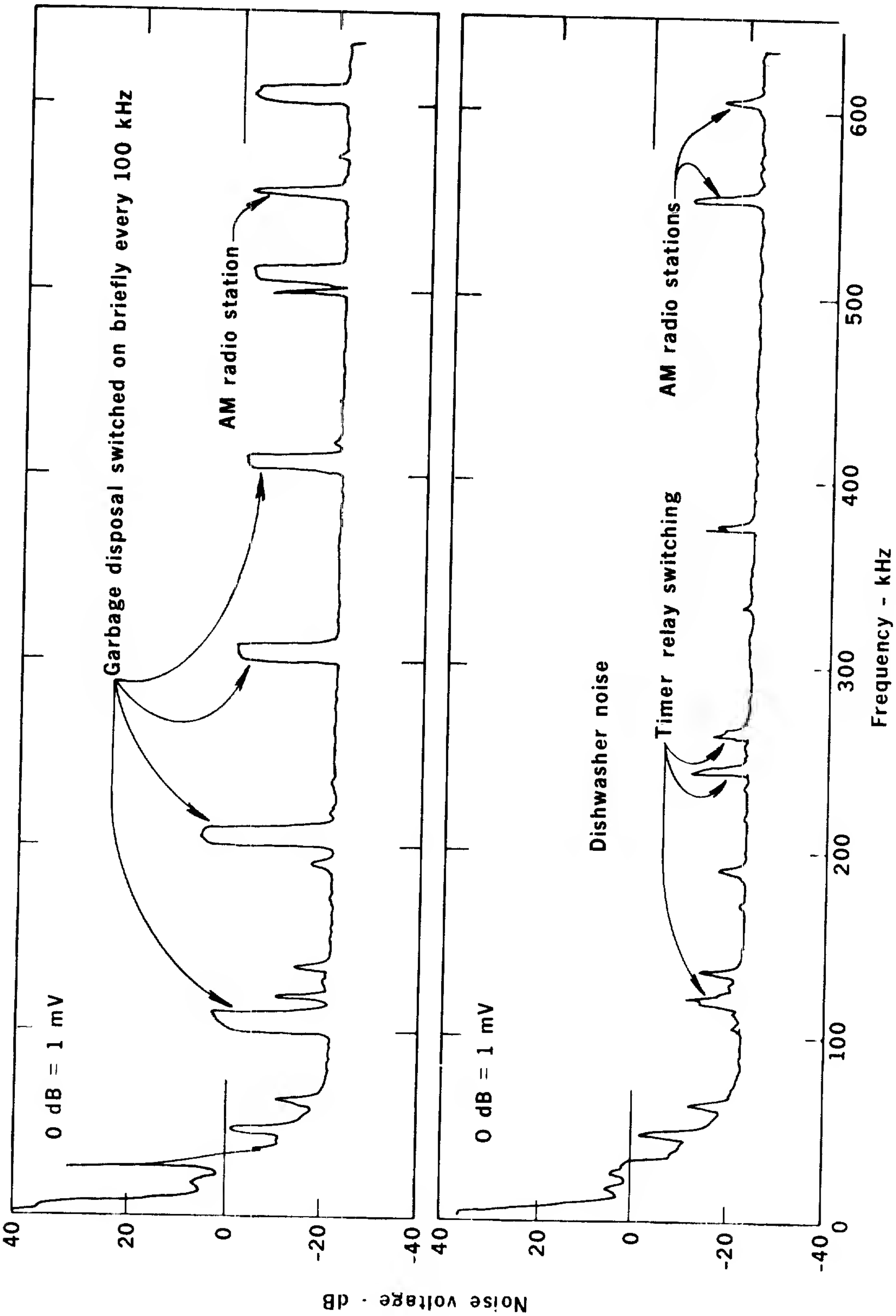

Figure 52. Garbage disposal and dishwasher noise taken at location 2; signals above 550 kHz are AM radio stations

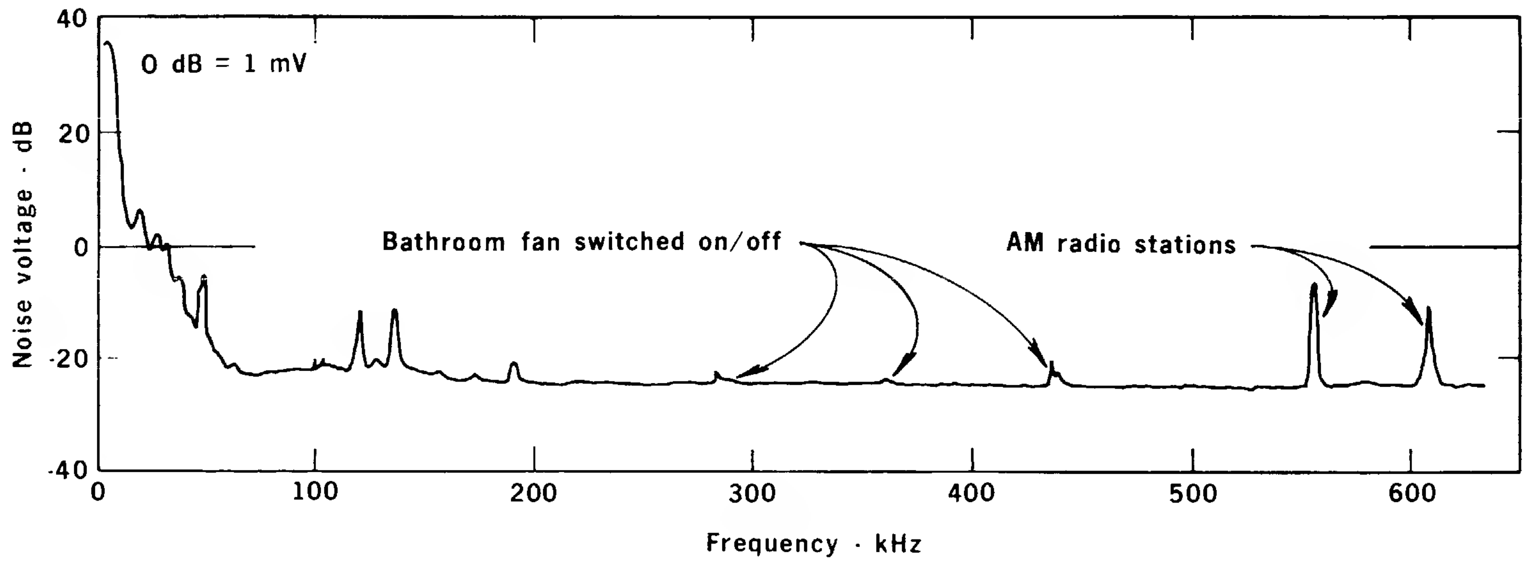

Figure 53. Noise, exhaust fan, taken at location 2; measured at breaker box—high to neutral

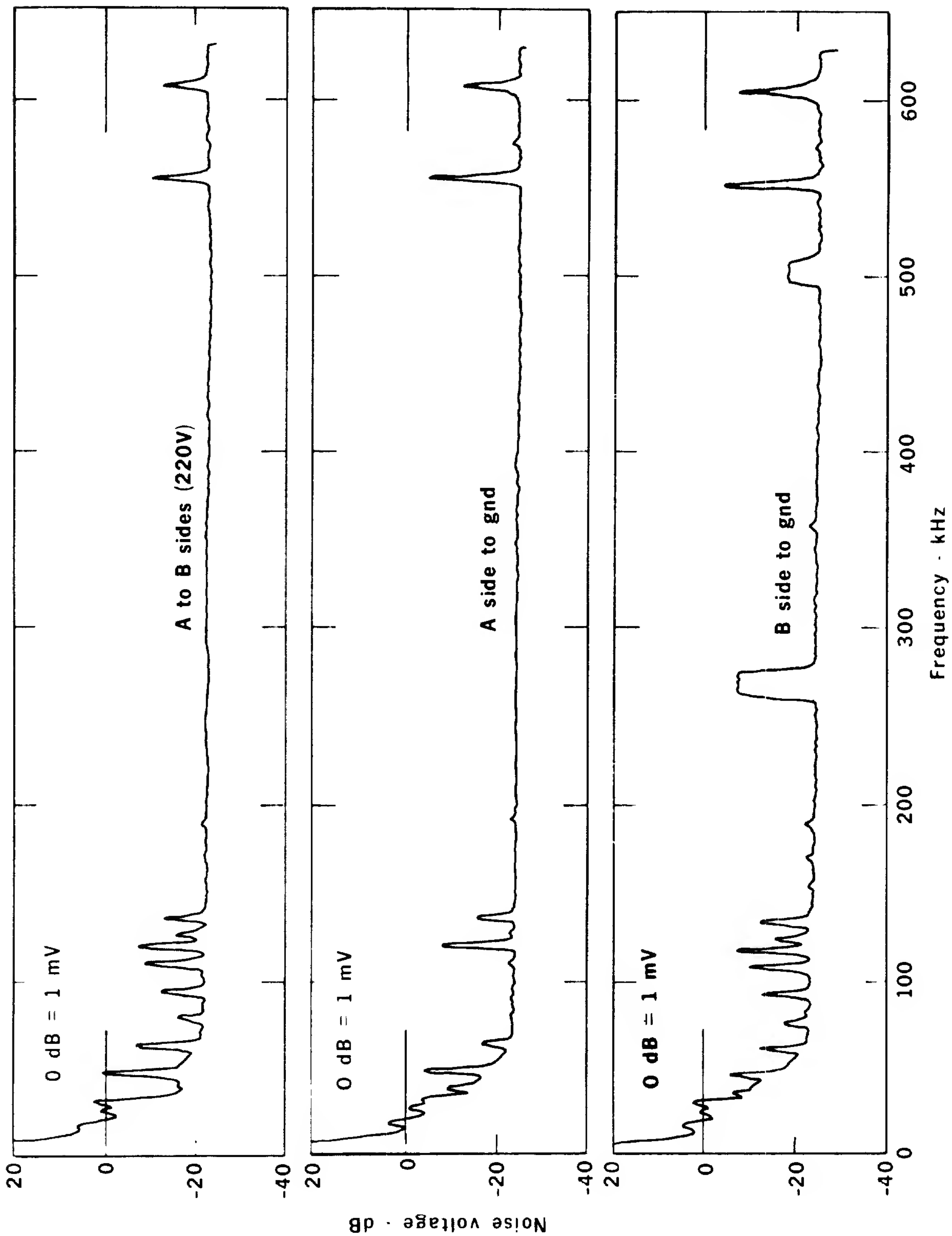

Figure 54. Air conditioner noise—location 2; measurements made at breaker box with only 4 active; signals above 550 kHz are substantiated AM radio stations

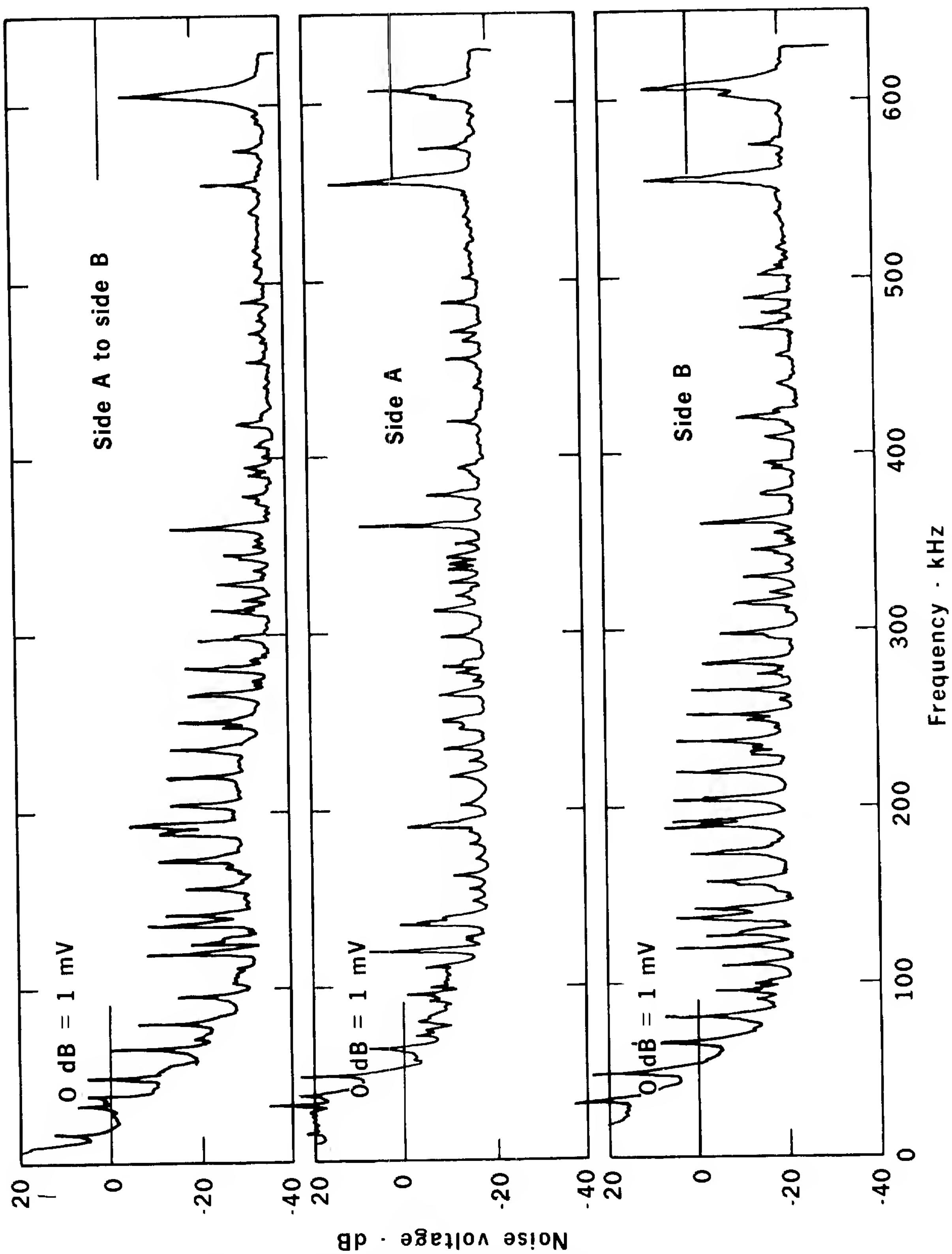

Figure 55. Location 1—Utility noise measured at breaker box with main breakers open; signals above 550 kHz are AM radio stations

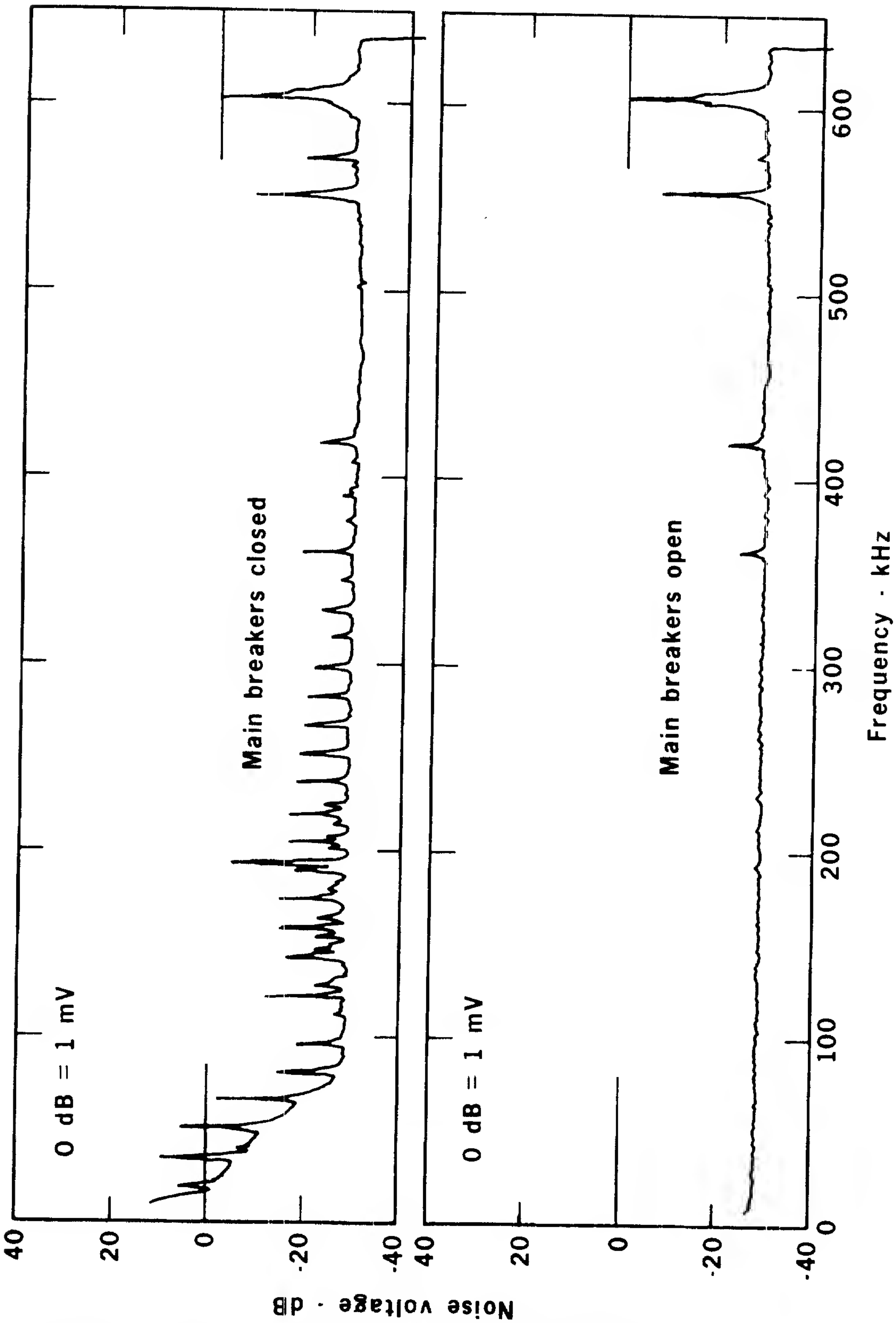

Figure 56. Location 1—Noise, outlet 3-2, no loads (signals above 550 kHz are radio stations)

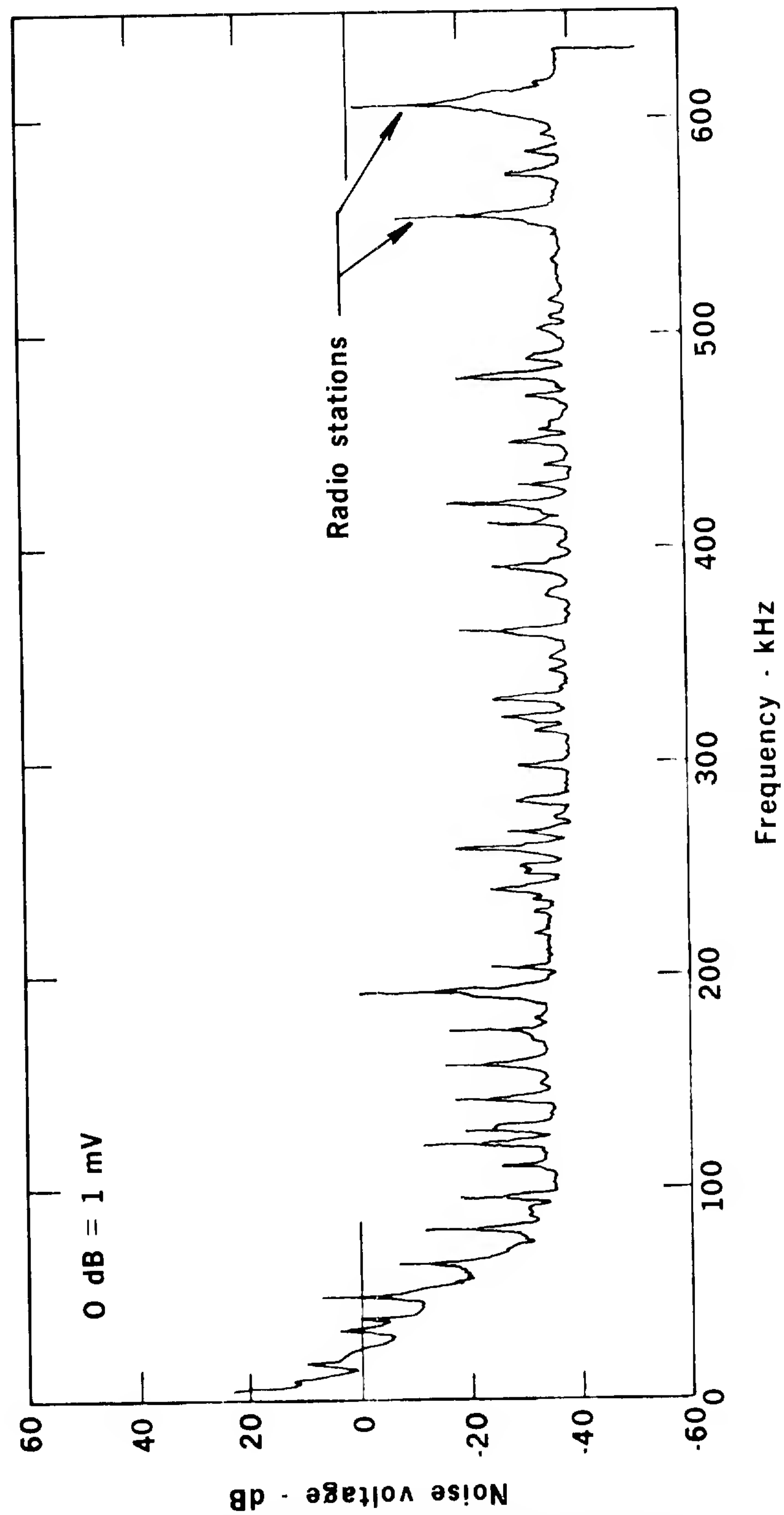

Figure 57. Location 1—Noise; outlet 3-2; no loads; main breakers closed (repeat of measurement in Fig. 56 with more sensitive scale)

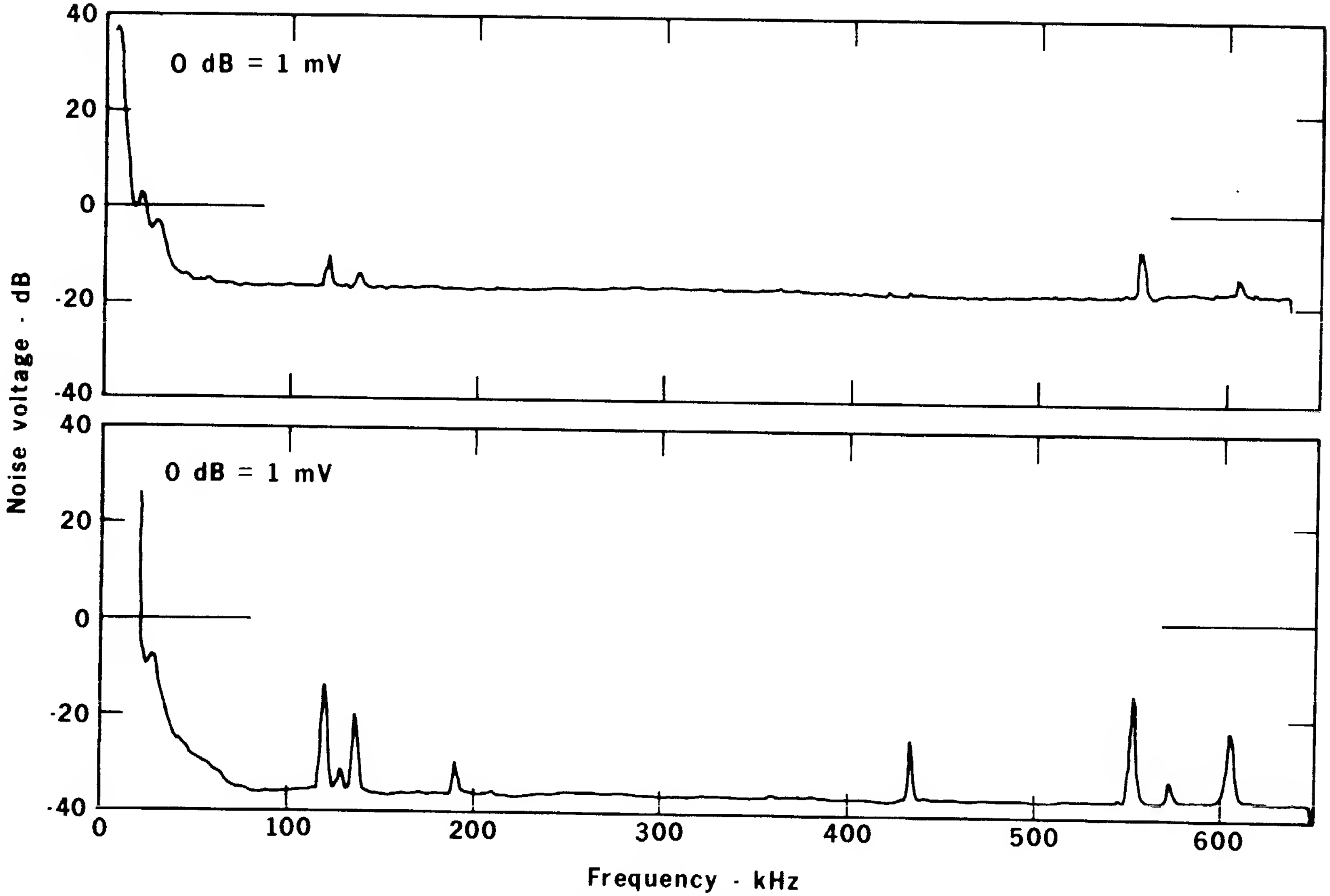

Figure 58. Location 2—Utility noise on the A side to neutral at the breaker box with main breakers open. Signals above 550 kHz are AM radio stations. Measurements are the same except for instrument sensitivity setting (lower graph has the data from the most sensitive setting).

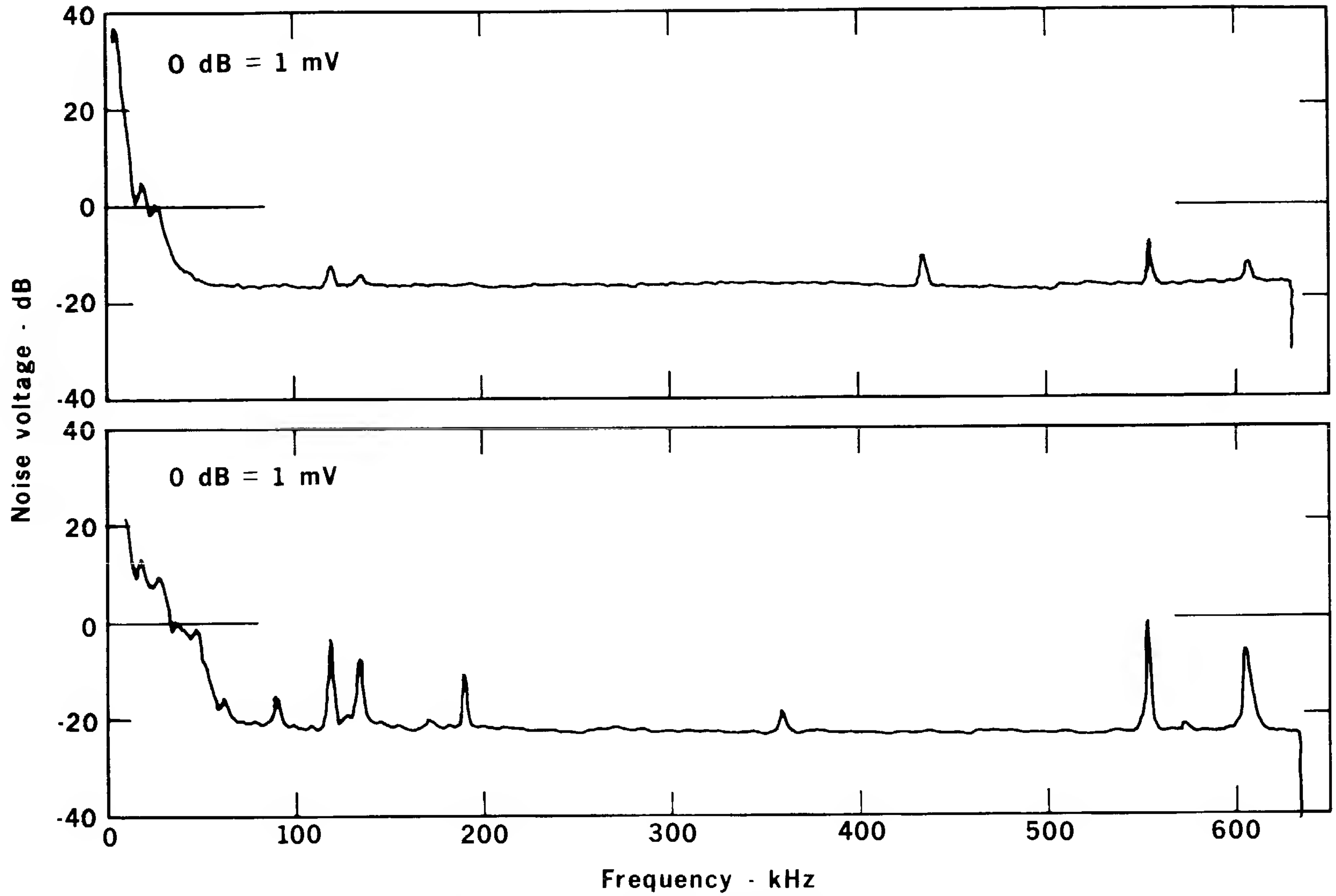

Figure 59. Location 2—Utility noise on the B side to neutral at the breaker box with main breakers open. Signals above 550 kHz are AM radio stations. Measurements are the same except for instrument sensitivity setting (lower graph has the data from the most sensitive setting).

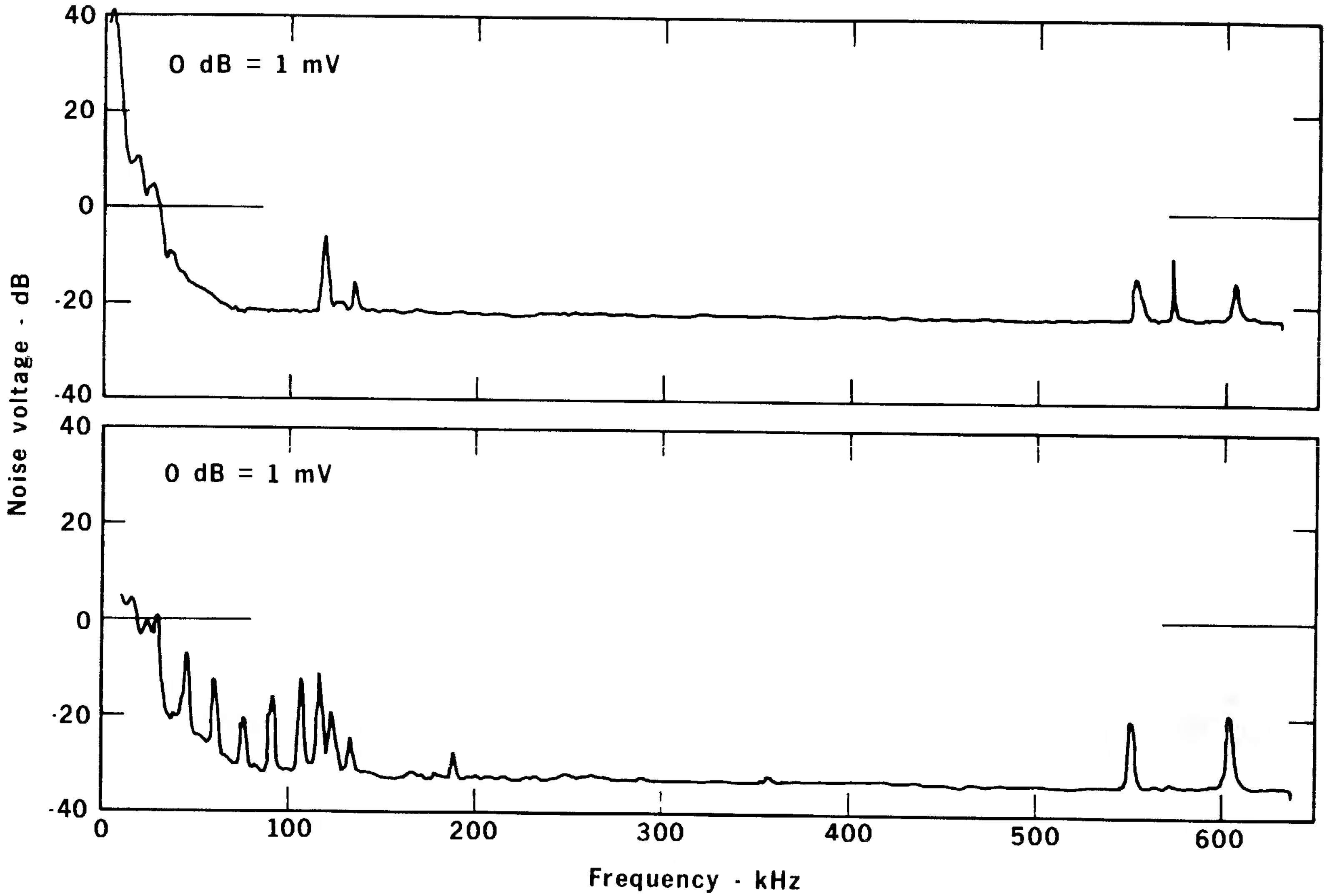

Figure 60. Location 2—Utility noise on the A side to the B side at the breaker box with main breakers open. Signals above 550 kHz are AM radio stations. Measurements are the same except for instrument sensitivity setting (lower graph has the data from the most sensitive setting).

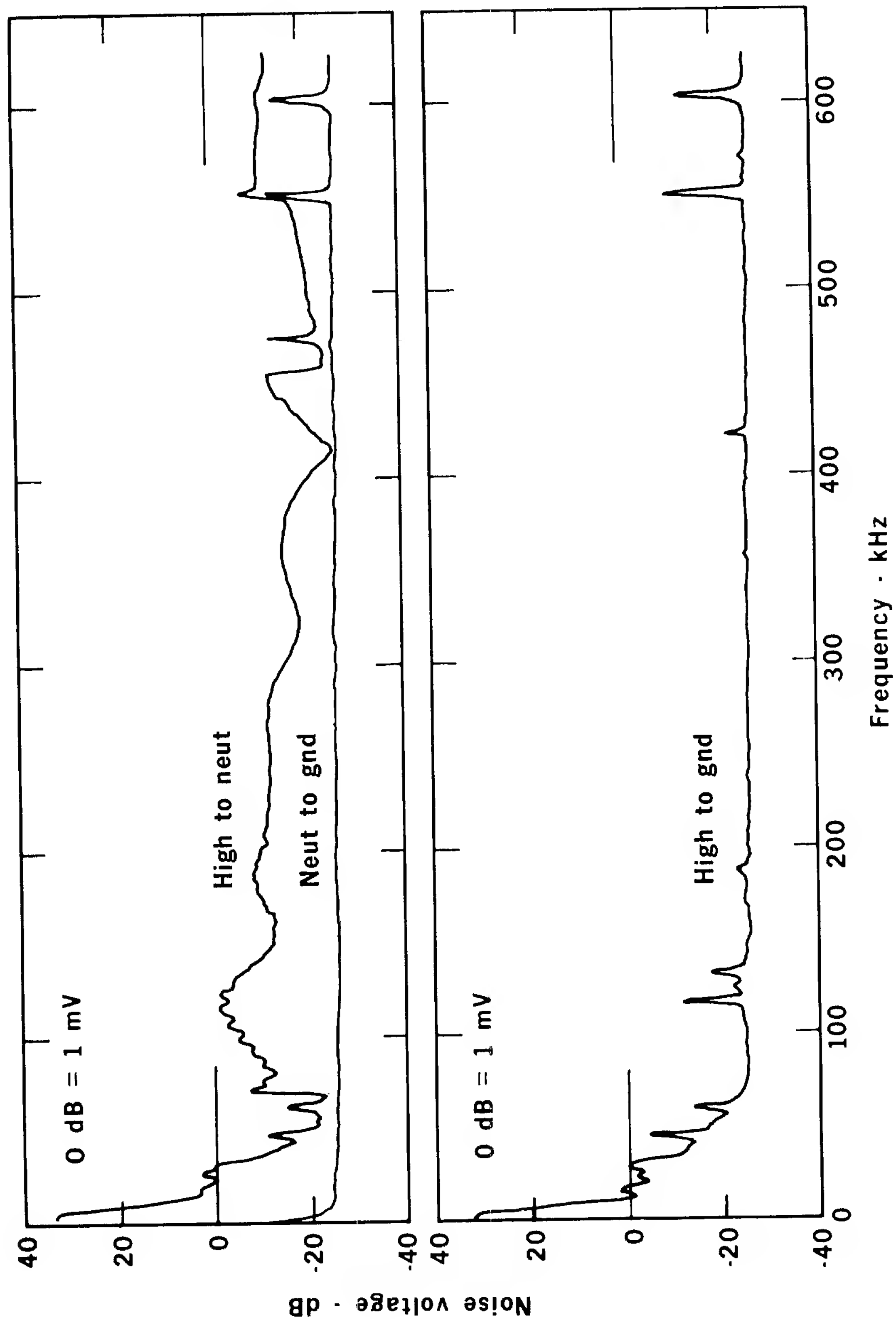

Figure 61. Location 2—Noise, outlet 9-6

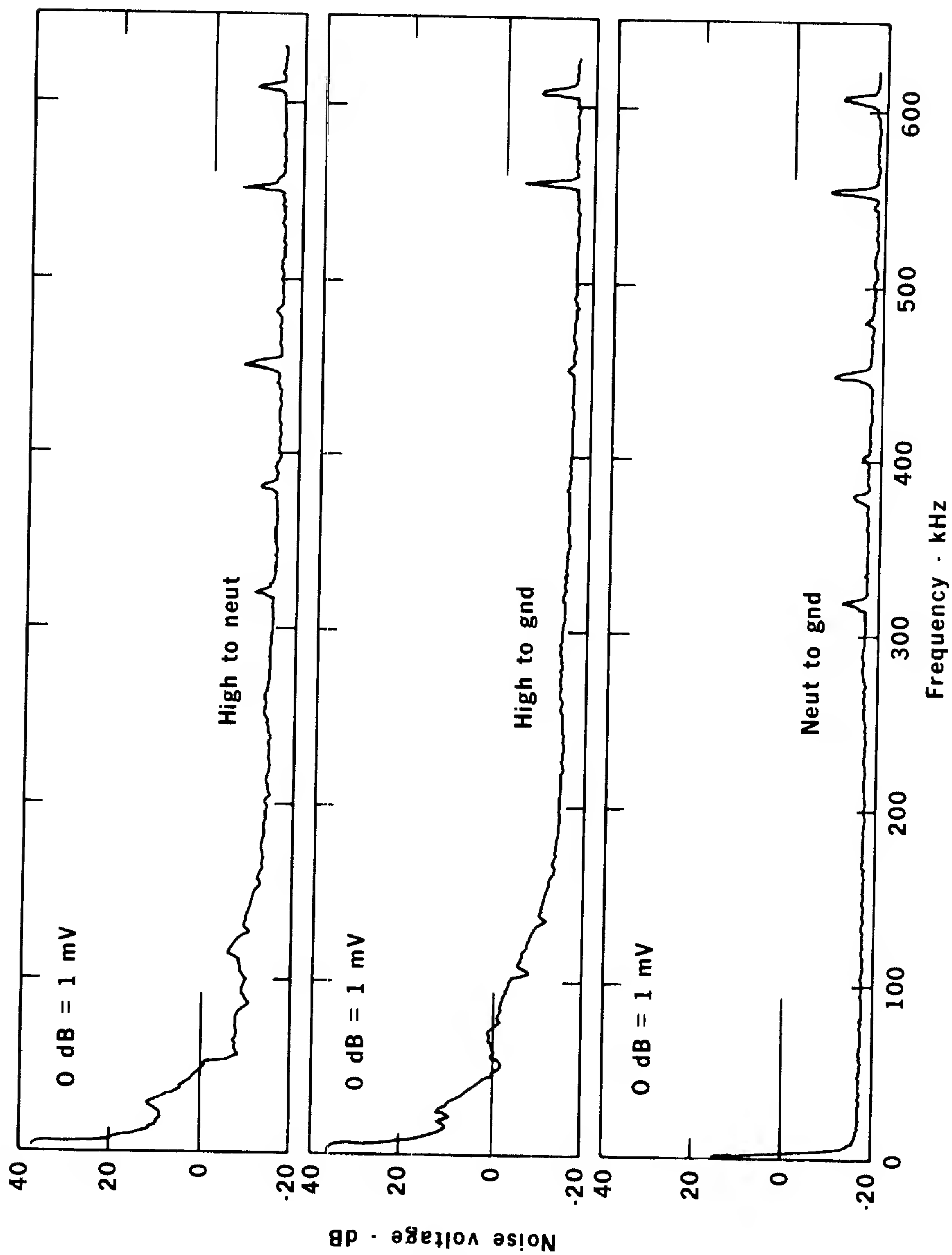

Figure 62. Location 3—Noise, floor 10, outlet B-16 (red phase)

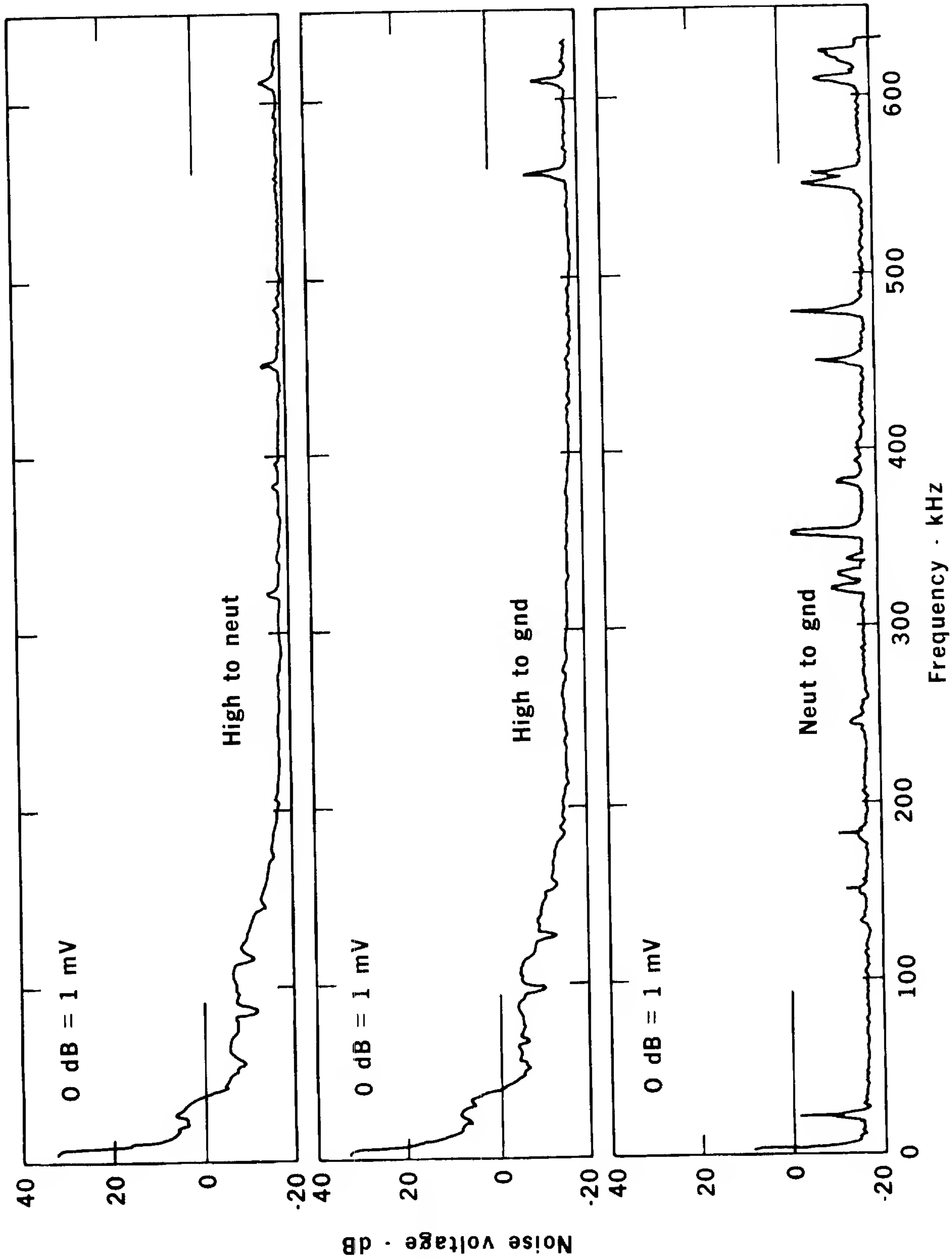

Figure 63. Location 3—Noise, floor 10, outlet B-18 (blue phase)

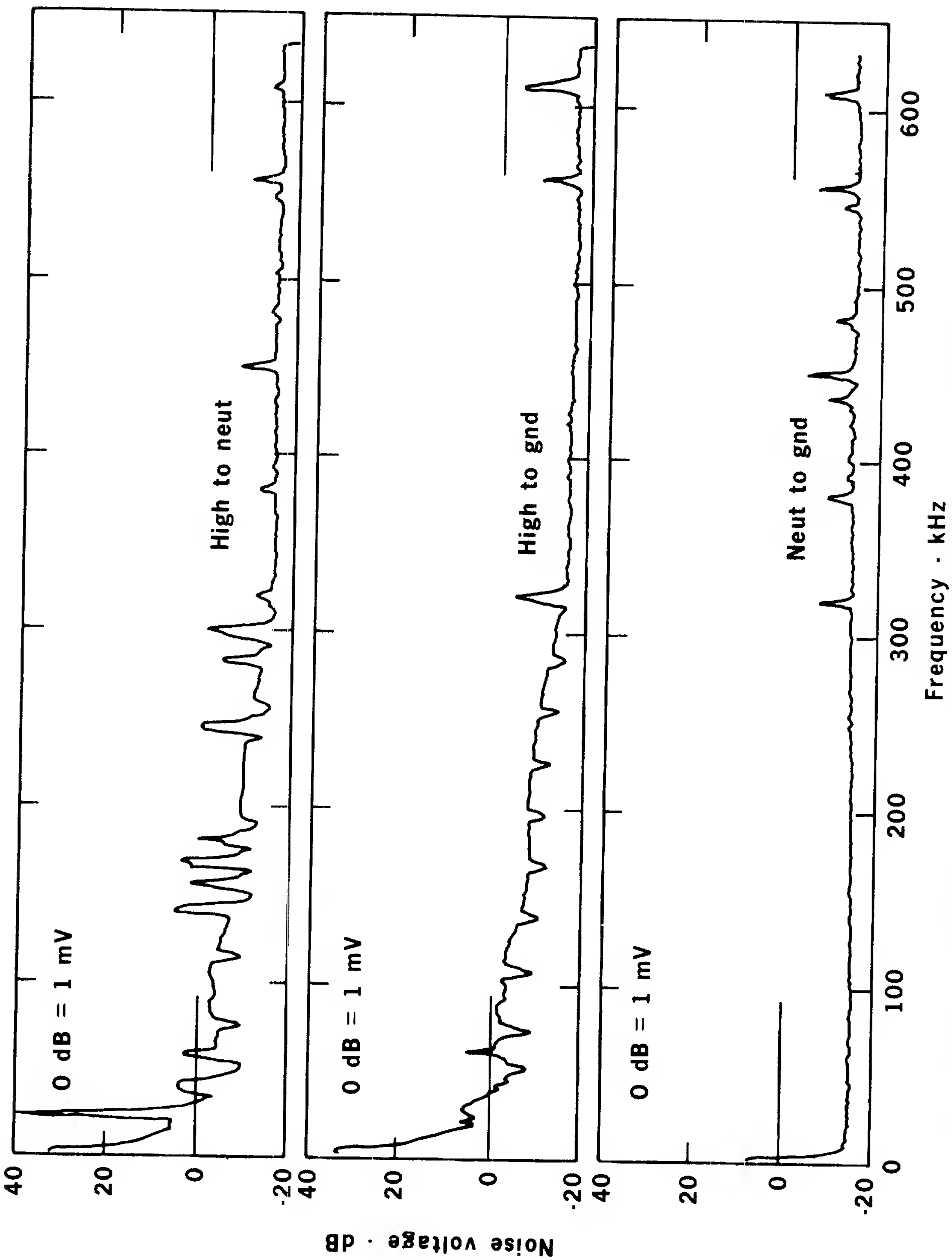

Figure 64. Location 3—Noise, floor 10, outlet B-14 (black phase)

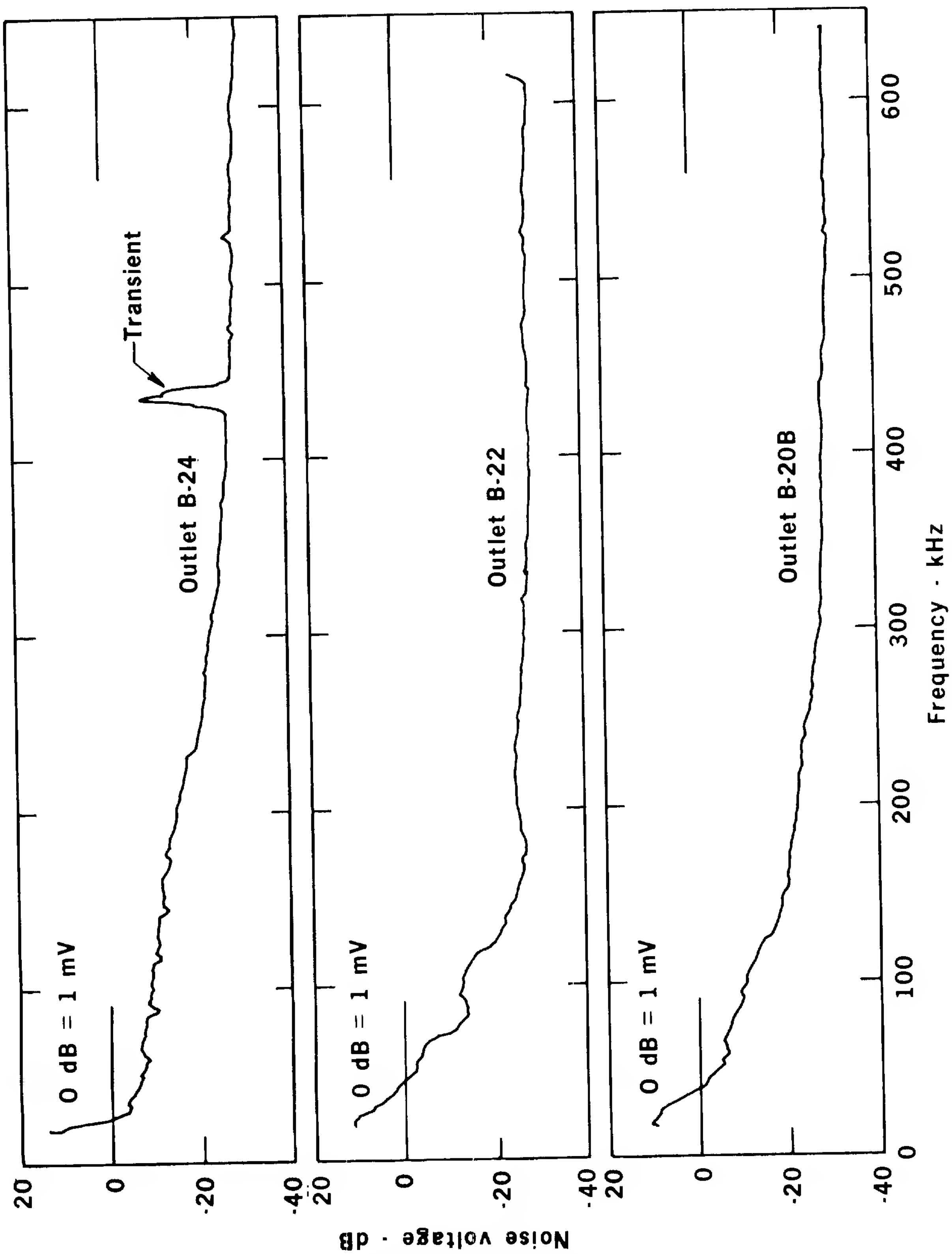

Figure 65. Location 3—Noise, floor 2, outlets B-24, B-22, B-20B. All measurements are high to neutral

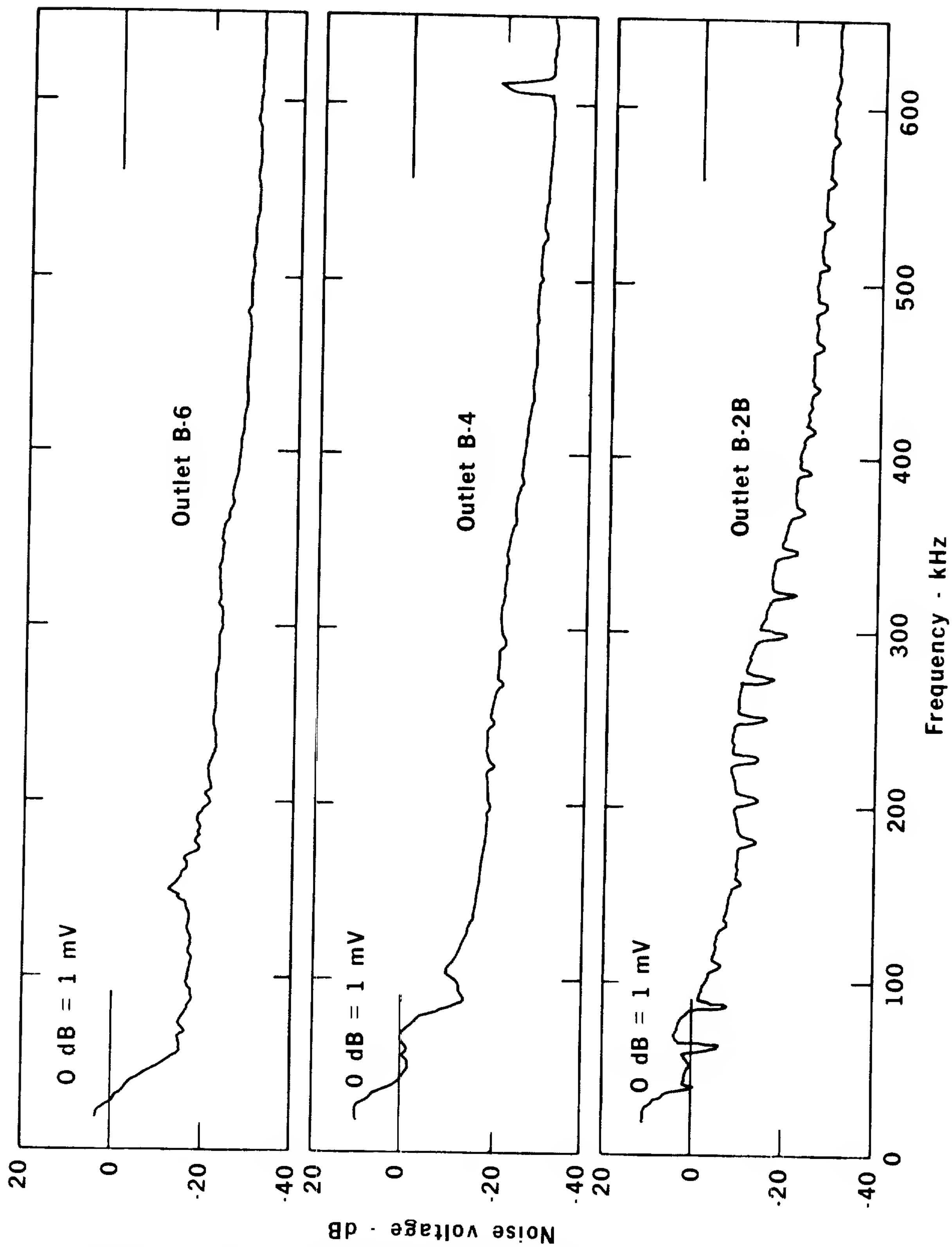

Figure 66. Location 3—Noise, floor 3, outlets B-4, B-2B, B-6; all measurements are high to neutral

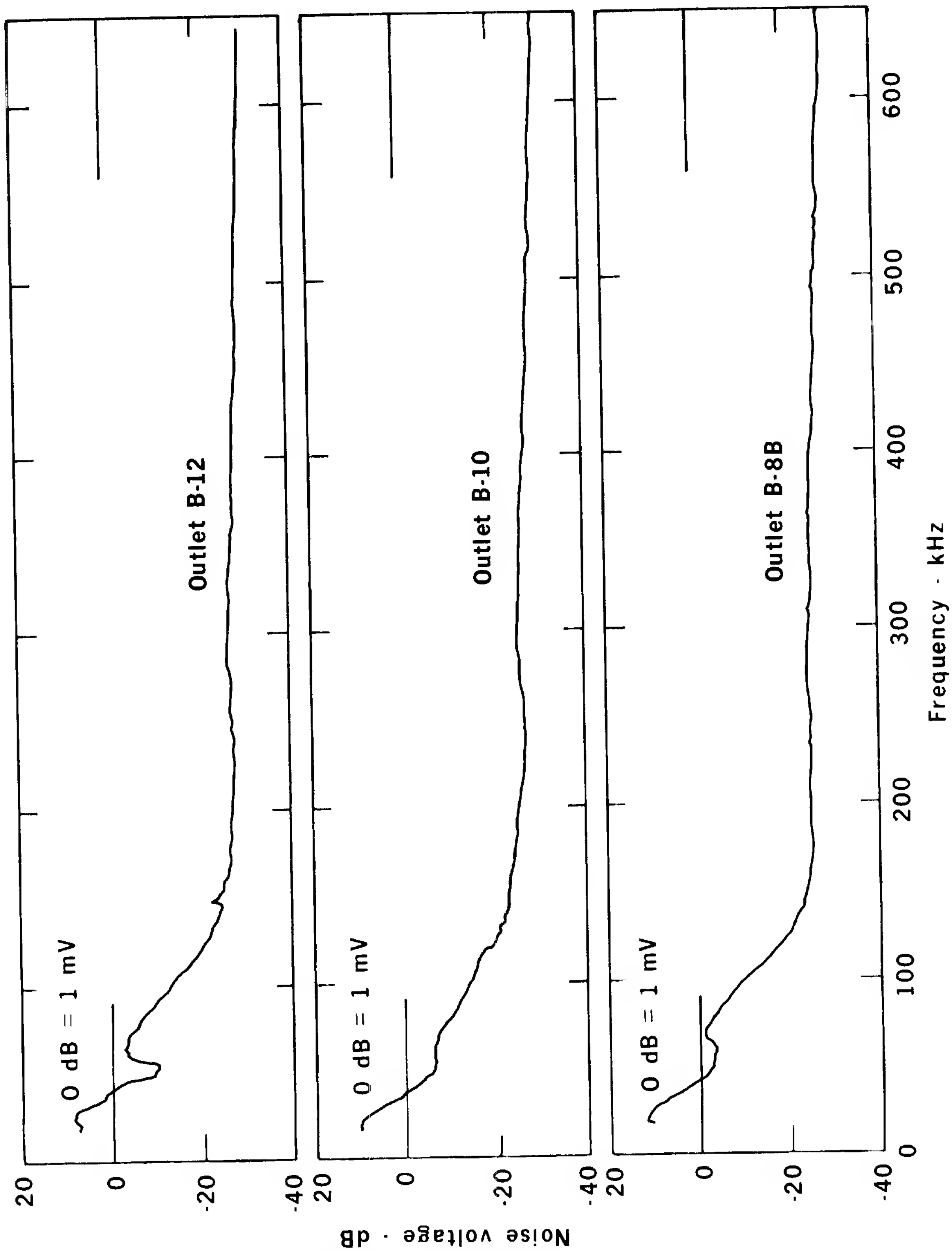

Figure 67. Location 3—Noise, floor 8, outlets B-12, B-10, B-88; all measurements are high to neutral

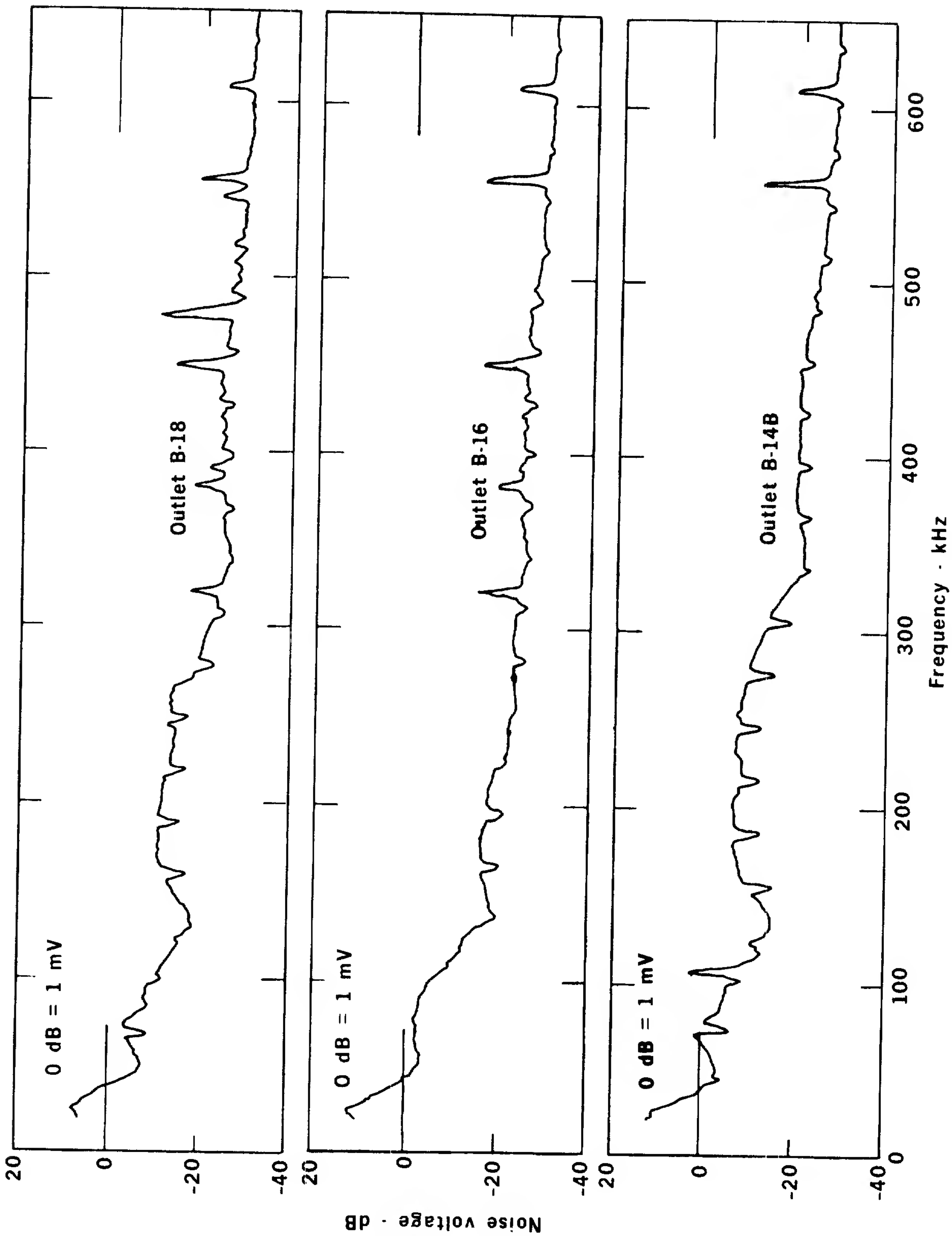

Figure 68. Location 3—Noise, floor 9, outlets B-18, B-16, B-14B; measured high to neutral; all breakers closed; signals above 550 kHz are AM radio stations

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DIRECTOR OF CENTRAL INTELLIGENCE
Security Committee
RESEARCH AND DEVELOPMENT SUBCOMMITTEE

31 OCT 1977

MEMORANDUM FOR: Chairman, Security Committee

SUBJECT : National Technical Threat Estimating Guide, Optical Communications Systems (C) Estimating Guide RD/6-76 (U)

25X1 1. [redacted] Attached for your use and retention is the report, National Technical Threat Estimating Guide, Optical Communications Systems. This report provides the detailed technical backup to the previously distributed report, National Technical Threat Estimates 1976-1981. This technical threat estimating guide is intended to provide the basic theoretical and factual foundation necessary to make sound technical estimates of the technical surveillance threat both for normal and unusual conditions. The estimating guide is expected to be used primarily by technical and engineering personnel in the conduct of detailed technical studies. This guide will also facilitate preparation of updated technical threat estimates as they become required.

25X1 2. [redacted] Other on-going studies will relate this technical threat to specific intelligence service capabilities insofar as they are known. Additional copies of this report are available upon request through each member agency's representative on the Research and Development Subcommittee or from the Executive Secretary, Research and Development Subcommittee.

25X1 [redacted] You may wish to forward this report to the NFIB for noting.

[redacted] 25X1

Chairman
Research and Development Subcommittee

Attachment:
As stated

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Secret

DIRECTOR
OF
CENTRAL
INTELLIGENCE

DCI Security Committee
Technical Surveillance
Countermeasures Subcommittee
Research & Development Subcommittee

National Technical Threat Estimating Guide—
Optical Communications Systems (C)
Estimating Guide RD/6-76 (U)

Secret

RD/6-76
November 1976

 Nº 2

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NOCONTRACT–	Not Releasable to Contractors or Contractor/Consultants
PROPIN–	Caution—Proprietary Information Involved
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Distribution of this document is limited. Further release must be approved by the Research and Development Subcommittee of the DCI Security Committee. Release to ERDA Contractors under the same conditions as apply to RD/1-76 authorized.

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ESTIMATE
1976-1981

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ESTIMATING GUIDE

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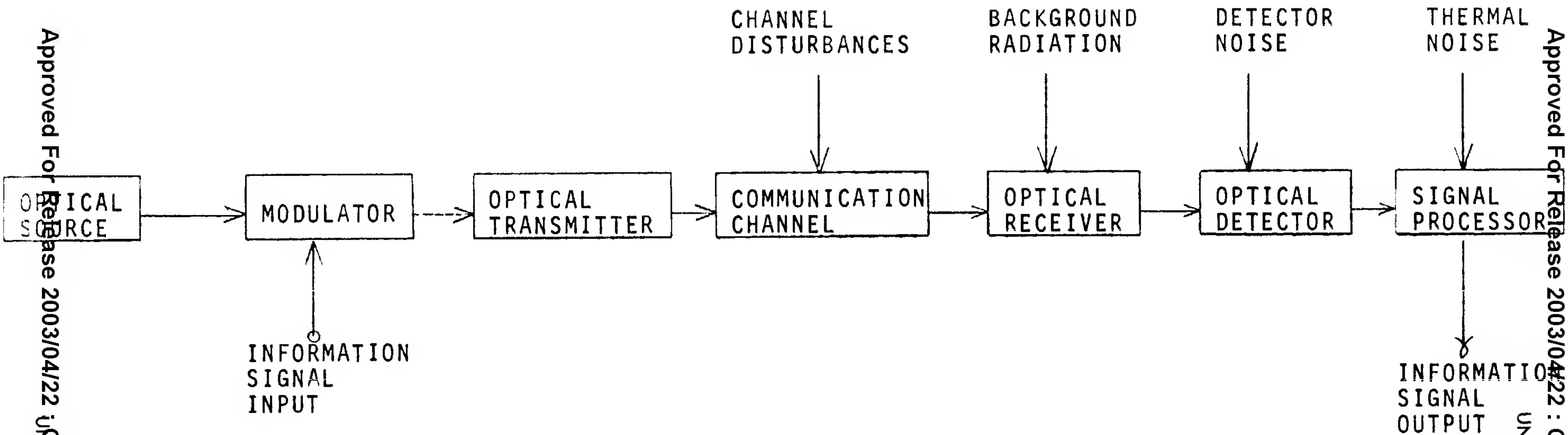

Figure 4. Schematic diagram of an optical communication system including important noise sources

Table I

Signal Modulation Schemes

Analog Methods

AM—analog Amplitude Modulation—carrier electric field amplitude is set proportional to information signal amplitude.

FM—analog Frequency Modulation—carrier instantaneous frequency is set proportional to information signal amplitude.

PM—analog Phase Modulation—carrier phase angle is set proportional to information signal amplitude.

IM—analog Intensity Modulation—carrier intensity is set proportional to information signal amplitude.

PL—analog Polarization Modulation—linear type: angle of linear carrier polarization with respect to reference axis is set proportional to information signal amplitude; circular type: ratio of carrier intensity in right-to-left polarization states is set proportional to information signal amplitude.

Pulse Methods

PAM—continuous or quantized Pulse Amplitude Modulation—pulsed carrier electric field amplitude is set proportional to information signal sample amplitude.

PFM—continuous or quantized Pulse Frequency Modulation—pulsed carrier frequency is set proportional to information signal sample amplitude.

PIM—continuous or quantized Pulse Intensity Modulation—pulsed carrier intensity is set proportional to information signal sample amplitude.

PDM—continuous or quantized Pulse Duration Modulation—pulsed carrier duration, with respect to start of sample period, is set proportional to information signal sample amplitude.

PPM—continuous or quantized Pulse Position Modulation—time delay of initiation of a short-duration carrier pulse is set proportional to information signal sample amplitude.

PRM—Pulse Rate Modulation—number of short-duration carrier pulses per unit time period is set proportional to information signal amplitude.

Digital Methods

PCM/IM(PCM/AM)—PCM Intensity (amplitude) Modulation, also called PCM/ASK, amplitude shift keying—carrier intensity (amplitude) is set at maximum to represent a "one" bit or at minimum to represent a "zero" bit of binary code of information signal sample amplitude.

PCM/FM—PCM Frequency Modulation, also called PCM/FSK, frequency shift keying—carrier frequency is set at one of two possible values to represent "one" or "zero" bit of binary code of information sample amplitude.

PCM/PM—PCM Phase Modulation, also called PCM/PSK, phase shift keying—carrier phase angle is set at a phase angle of zero or π radians with respect to a phase reference to represent "one" or "zero" bit of binary code of information signal amplitude.

PCM/PL—PCM Polarization Modulation—linear type: carrier is set in vertical polarization to represent "one" bit and horizontal polarization to represent "zero" bit of binary code of information signal sample amplitude; circular type: carrier is set in right circular polarization to represent "one" bit and left circular polarization to represent "zero" bit of binary code of information signal amplitude.

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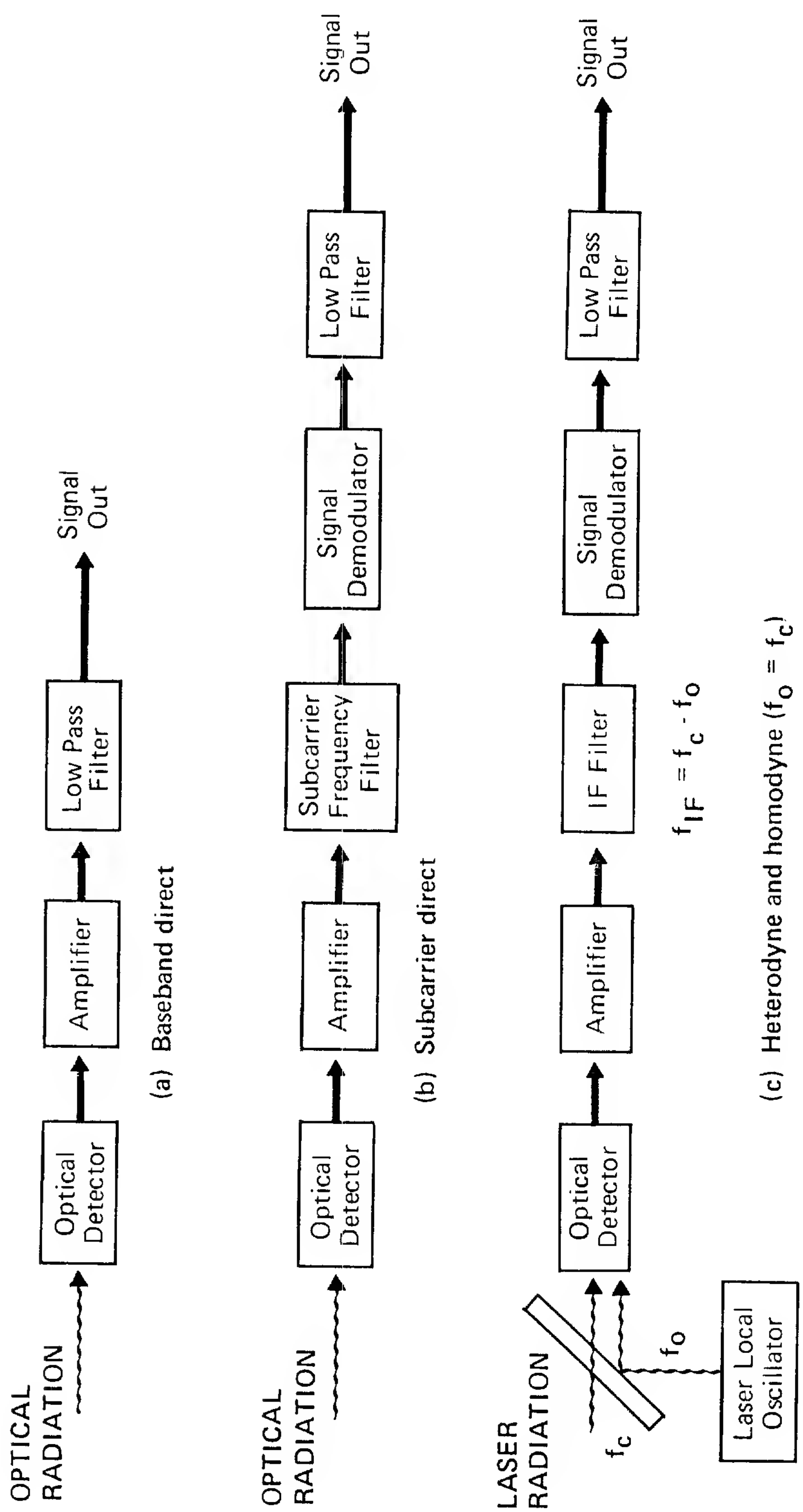

Figure 5. Three optical communication receiver types

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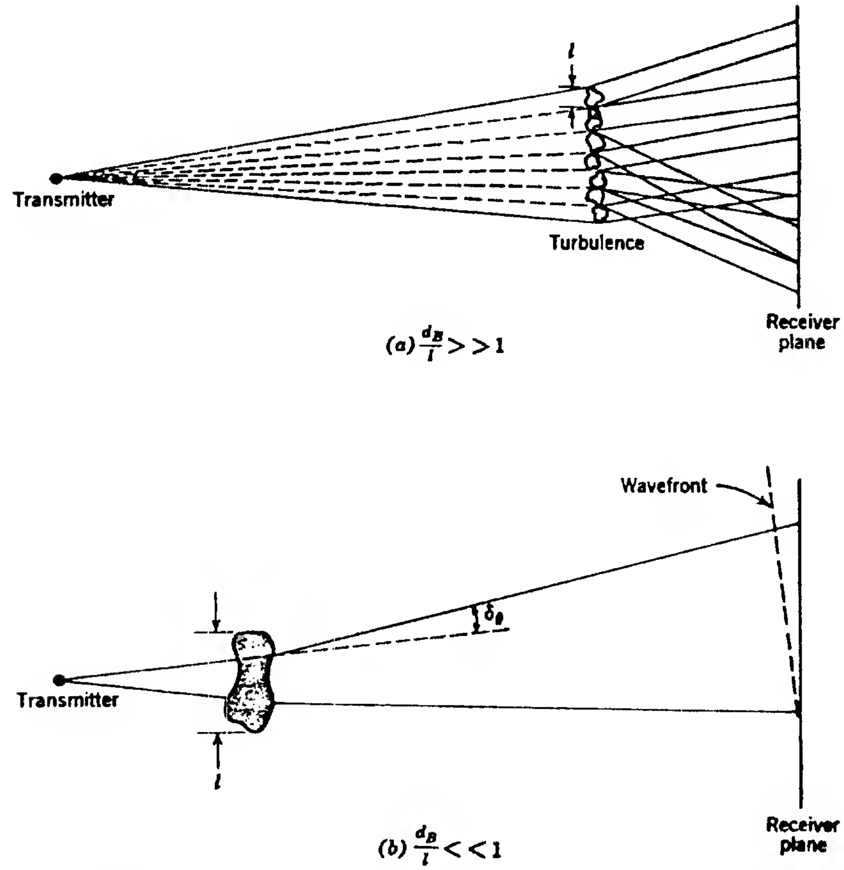


Figure 6. Atmospheric turbulence effects as a function of beam diameter and turbulence dimension

transmitted beam will usually cover several degrees while the induced spread is given approximately by δ_Θ (a few microradians at 1 km distance).

Beam scintillation results from the time-varying phase front distortions caused by atmospheric turbulence. Figure 8 shows intensity variations in the cross section of a laser beam after propagation through the atmosphere. Since the intensity distribution in Fig. 8 is time variable, the receiver aperture should be large compared to the bright spots so that aperture averaging prevents signal fading. The receiver diameter should be larger than r_o, the phase coherence dimension, as given in Fig. 9. For example, at 1 km distance and 1 micron wavelength, $r_o \approx 0.5$ m for $C_n = 10^{-7}$ m^{-13} (intermediate to strong turbulence—see Fig. 9 for C). Although r_o increases with decreasing range, the ratio of bright spot intensity to dark spot intensity decreases so that shorter ranges do not actually require bigger receivers to prevent signal fading. Signal fading due to beam scintillation should not be a problem up to at least 1 km distance with most practical receivers.

For heterodyne or homodyne detection, one would also have to consider spatial coherence degradation. No significant increase in signal-to-noise ratio can be obtained with a single detector in these modes of operation for receiver apertures larger than r_o. Thus atmospheric turbulence can severely degrade the system performance for these detection methods.

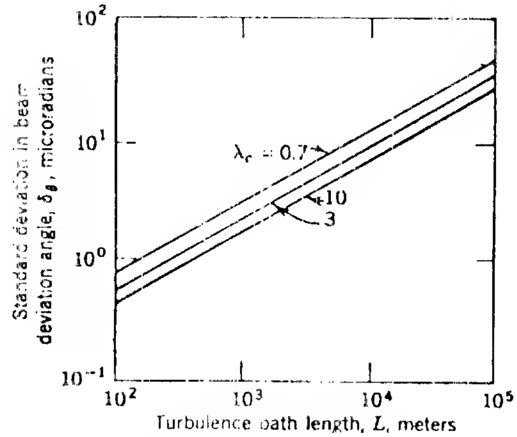


Figure 7. Standard deviation in beam deviation angle of a phase coherent portion of a laser beam due to intermediate atmospheric turbulence

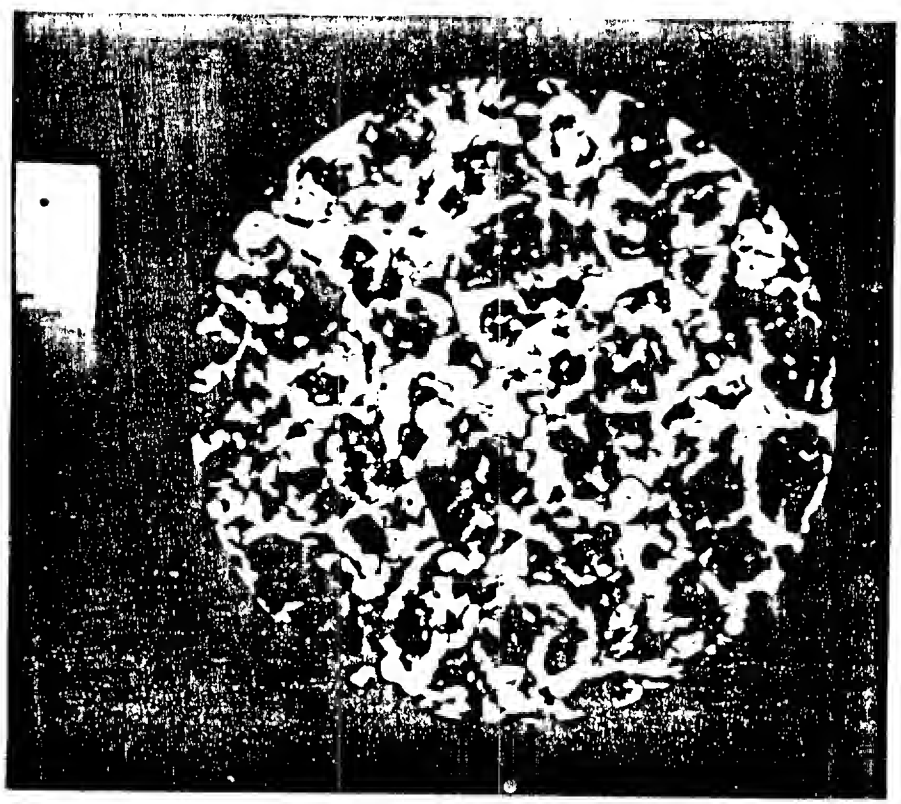


Figure 8. Laser beam cross section intensity variations

In addition to the effects just discussed, one must also consider signal attenuation due to atmospheric absorption and scattering. Signal transmission as a function of path length is given by

$$\tau_a = \exp\{-\alpha L\} \tag{2}$$

where L is the path length through the atmosphere and α is the attenuation coefficient. Ozone absorption is the prime attenuator in the ultraviolet region of the spectrum, aerosol scattering in the visible, and water vapor and carbon dioxide absorption in the infrared. Fig. 10 gives the attenuation coefficient due to scattering and ozone absorption from 0.2 to 4μ wavelength for standard clear atmosphere; Fig. 11 includes curves for other atmospheric conditions over the range 0.4 to 4μ. The effects of molecular absorption (H_2O and CO_2) are shown in Figs. 12a through 12e, which are transmission curves for a 0.3 km path and 1.9 cm/km precipitable water (80% humidity, 26°C). Although atmospheric transmission depends on the level of precipitable water in the air, the data in these figures should be useful in determining the wavelengths which pose the greatest threat. For path lengths L other than 0.3 km, the transmission due to H_2O and CO_2 can be calculated by

$$\tau'_a = (\tau_0)^k$$

where k = L/0.3 km and τ_0 is the transmission from Fig. 12. The overall transmission is the product of the ozone/aerosol transmission τ_a and the H_2O/CO_2 transmission τ'_a at the wavelength of interest.

One may summarize this discussion of atmospheric effects by noting that for reasonable sized receiver apertures and path lengths up to at least 1 km,

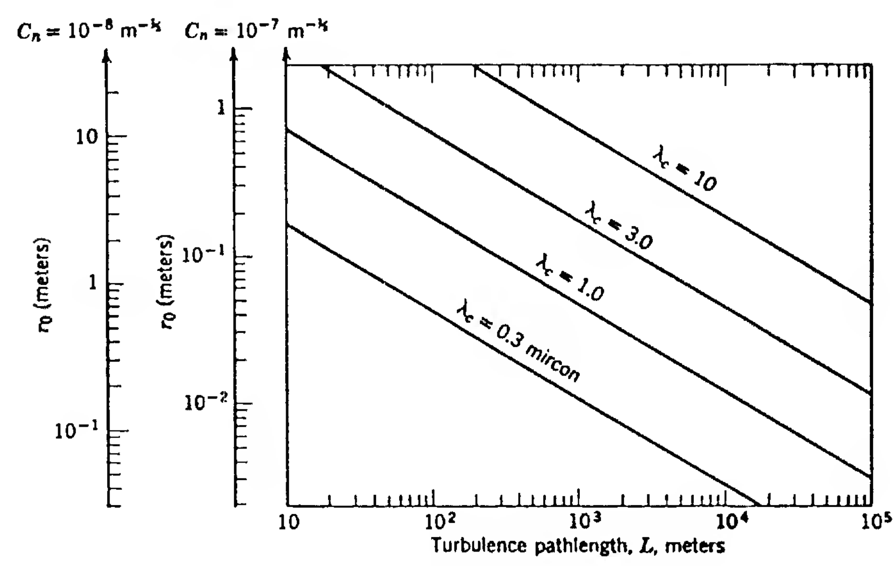


Figure 9. Dependence of r_0 on transmission wavelength, turbulence pathlength, and turbulence structure constant $C_n \approx 4 \times 10^{-8}$ and 5×10^{-7} $m^{-1/3}$ for intermediate and strong turbulence, respectively, where C_n is a measure of the strength of the turbulence

atmospheric turbulence can be neglected. And, in addition, if the wavelength is picked to avoid strong molecular absorptions, the beam will propagate over this same 1 km path with little atmospheric attenuation.

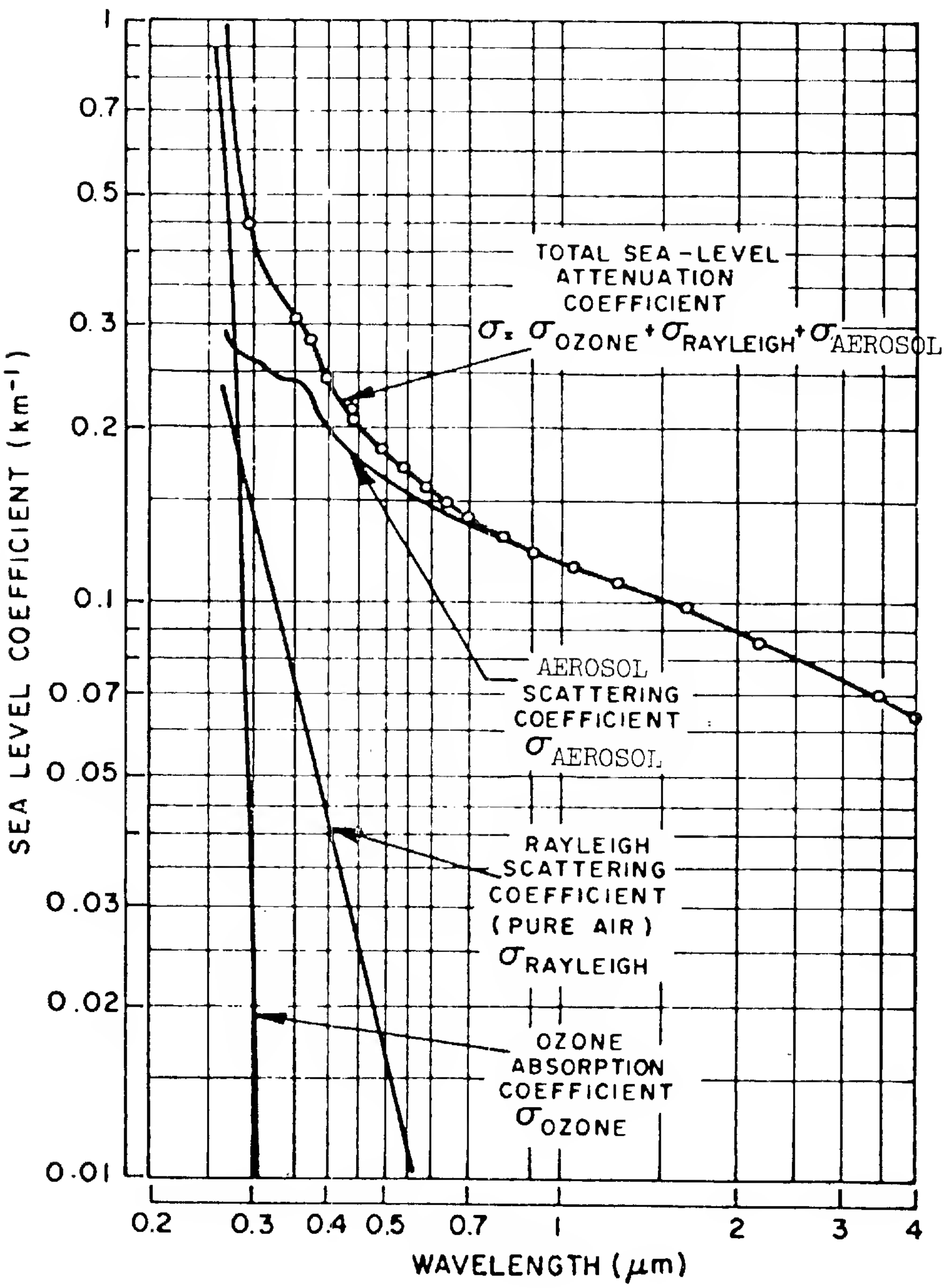


Figure 10. Calculated atmospheric attenuation coefficients for horizontal transmission at sea level in a model clear standard atmosphere (neglects absorption by water vapor and carbon dioxide)

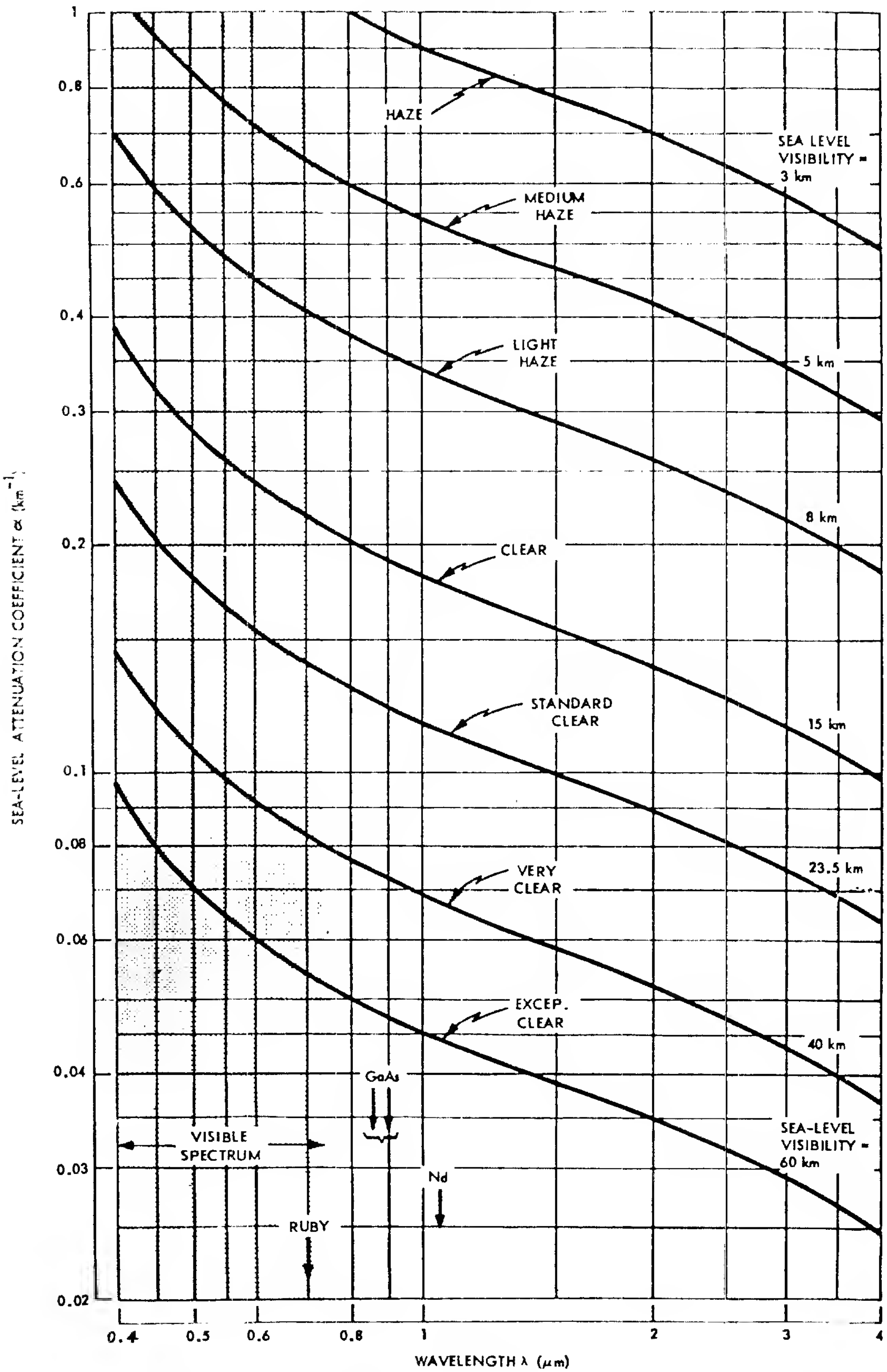


Figure 11. Approximate variation of attenuation coefficients with wavelength at sea level for various atmospheric conditions (neglects absorption by water vapor and carbon dioxide)

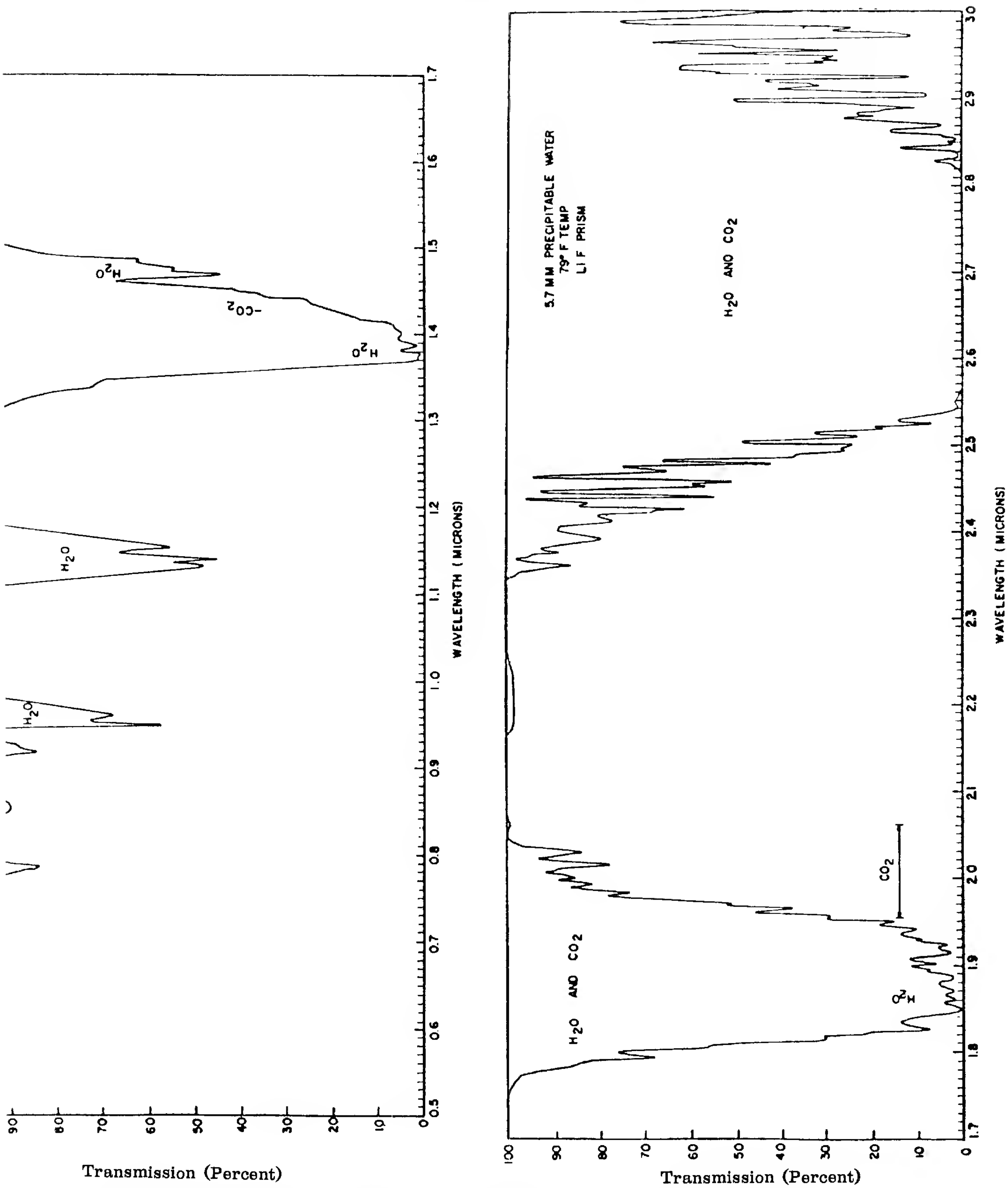


Figure 12a. Atmospheric transmission versus wavelength for a 0.3 km path and 1.9 cm/km precipitable water

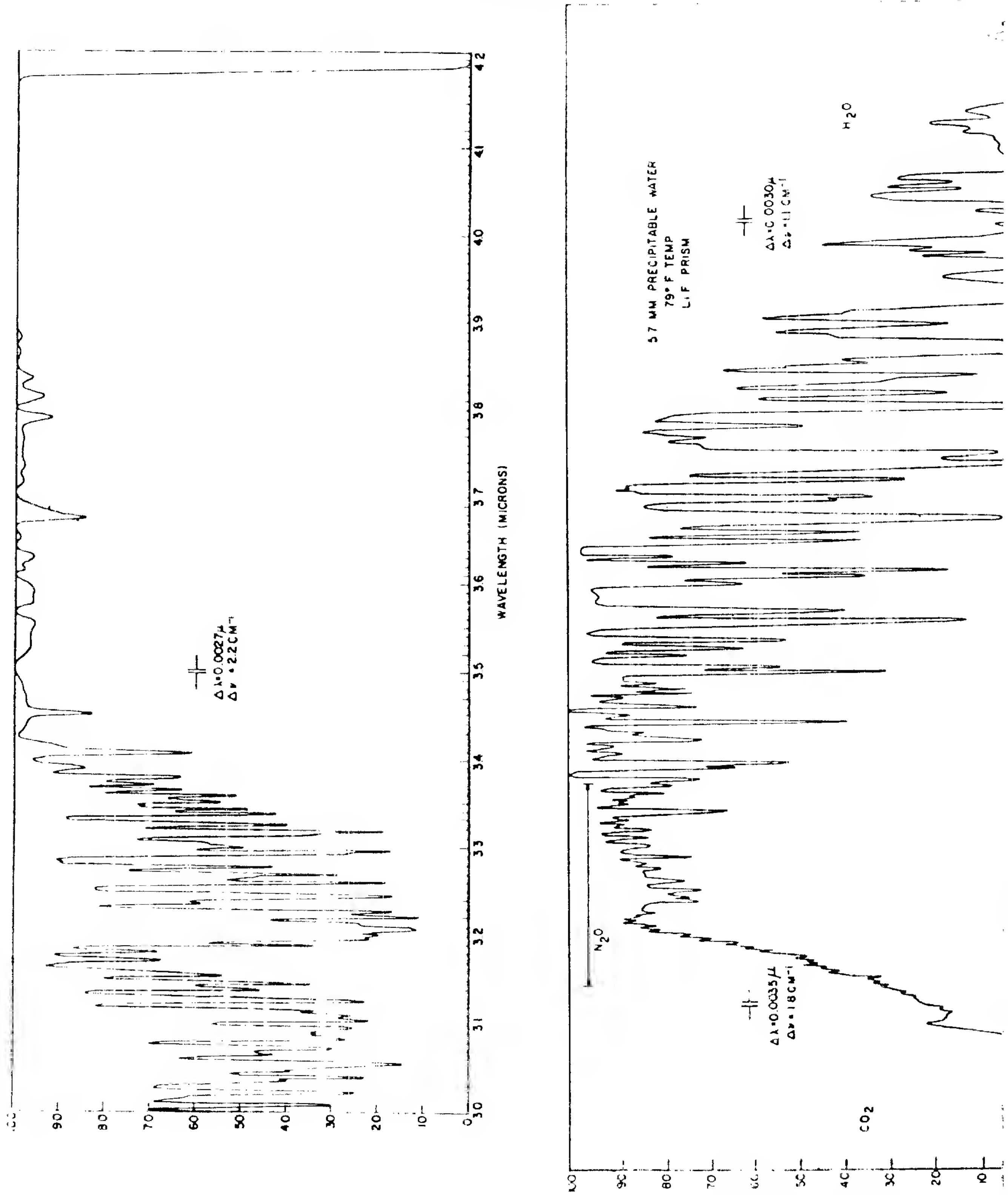


Figure 12b. Atmospheric transmission versus wavelength for a 0.3 km path and 1.9 cm/km precipitable water

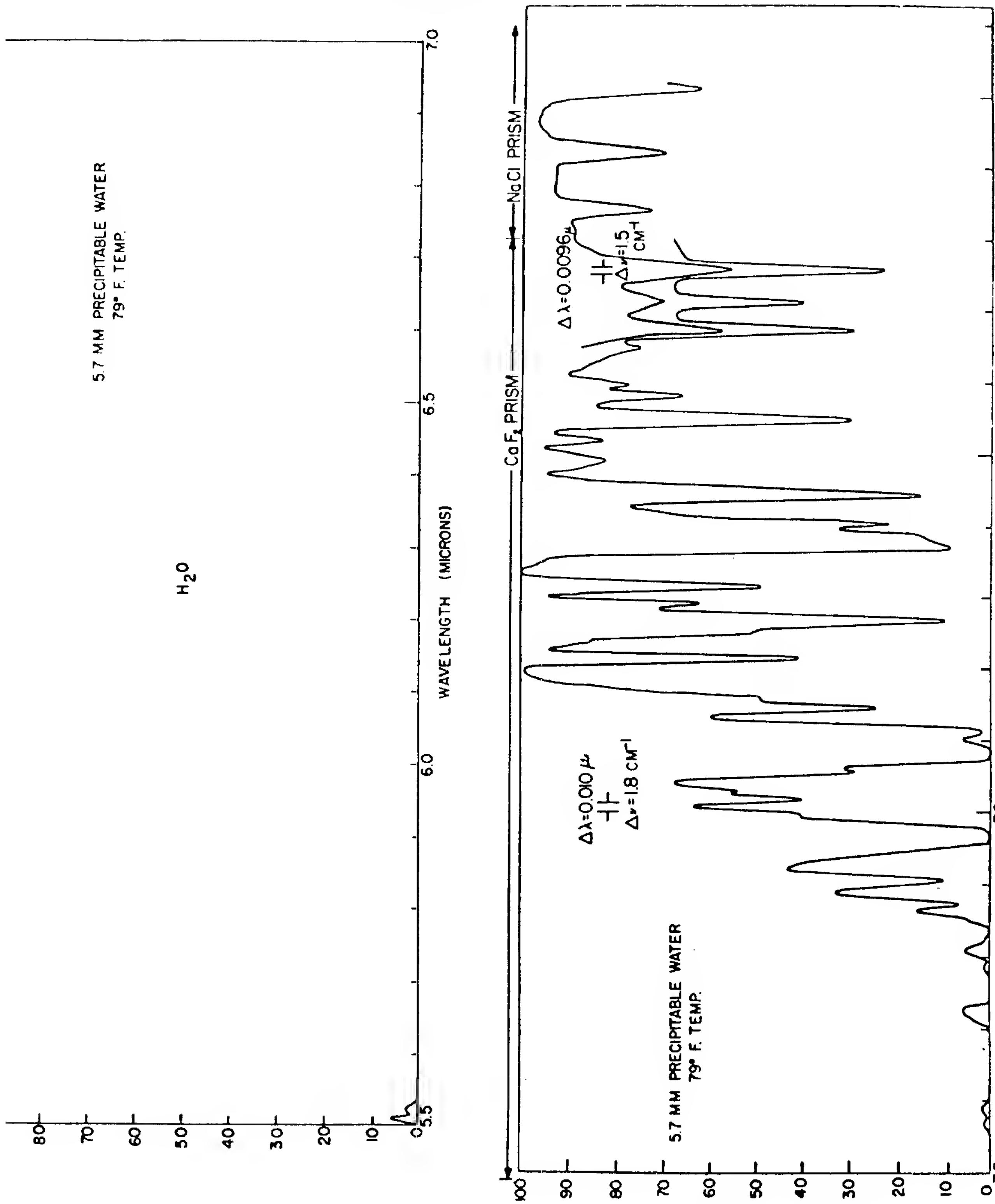


Figure 12c. Atmospheric transmission versus wavelength for a 0.3 km path and 1.9 cm/km precipitable water

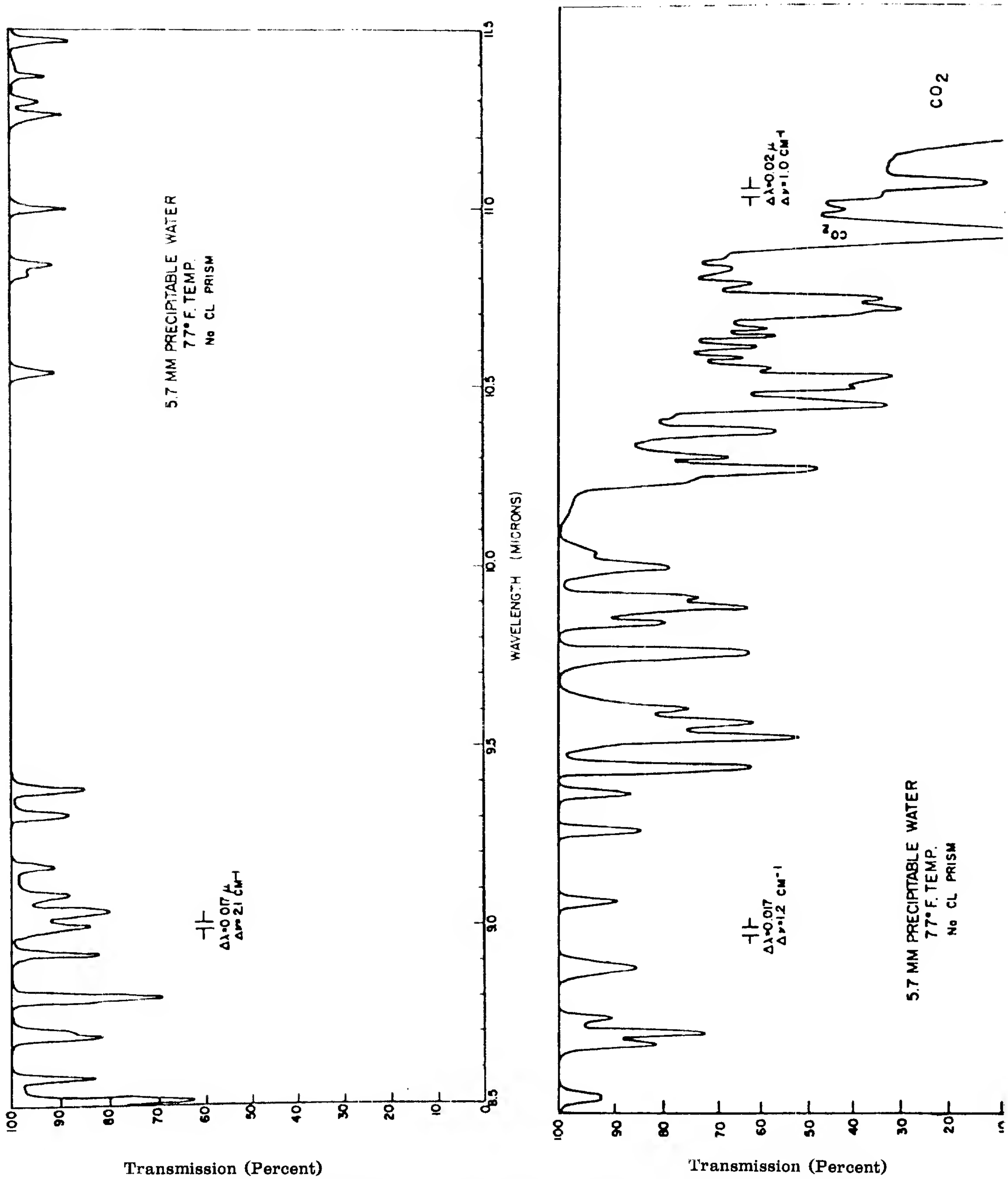
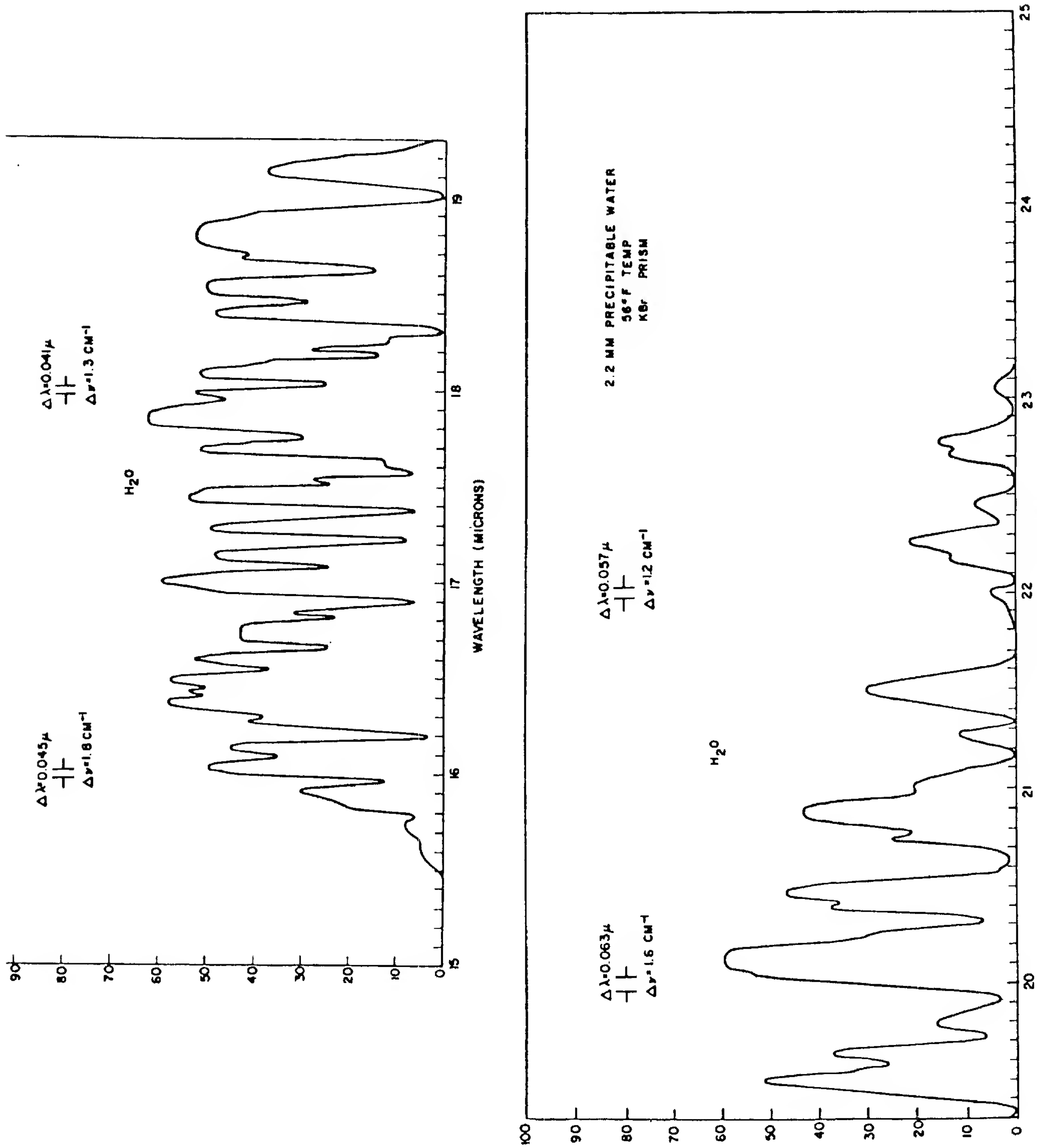


Figure 12d. Atmospheric transmission versus wavelength for a 0.3 km path and 1.9 cm/km precipitable water



Transmission (Percent) Transmission (Percent)

Figure 12e. Atmospheric transmission versus wavelength for a 0.3 km path and 1.9 cm/km precipitable water

2.3 NOISE

For a discussion of noise sources and their effect on carrier power P_c required to achieve a given signal-to-noise ratio, it is convenient to solve Eq. 1 for P_c explicitly. The result is shown as Eq. 4 (power in watts):

$$P_c = 2P_0 \left[1 + \left(1 + \frac{P_b}{P_0} + \frac{I_d}{I_0} + \frac{T}{T_0} \right)^{1/2} \right] , \tag{4}$$

where P_0, I_0 and T_0 are characteristic power, current and temperature, respectively, and are given by

$$P_0 = \frac{2.0 \times 10^{-19}}{\eta \lambda_c} \left(\frac{B_0 \; SNR}{m^2} \right) , \tag{5a}$$

$$I_0 = 1.6 \times 10^{-19} \left(\frac{B_0 \; SNR}{m^2} \right) , \tag{5b}$$

and

$$T_0 = 9.3 \times 10^{-16} \; G^2 R_\ell \left(\frac{B_0 \; SNR}{m^2} \right) ; \tag{5c}$$

and

P_b is the received background light intensity (watts), I_d the photoconverter dark current (amperes), and T the receiver temperature (Kelvin). The three dimensionless ratios in Eq. 4 determine the strength of the noise sources with which we will be concerned. Other parameters are:

- G photomultiplier internal gain,
- R_ℓ receiver load resistor (ohms),
- η quantum efficiency of the photodetector,
- λ_c wavelength of the carrier light beam (microns),
- B_o signal (output filter) bandwidth (hertz),
- SNR signal-to-noise ratio, and
- m depth of modulation.

It is apparent from inspection of Eq. 4 that the minimum carrier power for a given SNR value is achieved when P_b, I_d and T are small. When they are small enough to be neglected, P_c approaches a value given by

$$P_c = 4P_0 \text{ (signal shot noise limit).} \tag{6}$$

The best systems are designed for negligible noise contributions from dark current and thermal noise, and the contribution from background light is kept as low as possible. We will consider thermal noise and dark current here, however.

Thermal noise usually dominates when using a unit gain (G = 1) photodetector (e.g., a silicon photodiode). At room temperature the thermal noise power in a 2.7 kHz bandwidth (the band for voice communications covers from about 300 Hz to 3000 Hz) is

$$4kTB_o = 4.4 \times 10^{-17} \text{ watts.} \tag{7}$$

Assuming G = 1 and thermal noise dominates, one can calculate the minimum detectable carrier power P_c by retaining only the final noise term in Eq. 4:

$$P_c \approx 2P_o \left[\frac{T}{T_o}\right]^{1/2}$$

$$= \frac{1.32 \times 10^{-11}}{m\eta\lambda_c} \left[\frac{B_o \cdot SNR \cdot T}{G^2 R_\ell}\right]^{1/2} \tag{8}$$

(thermal noise limited)

For typical values like $\eta = 0.5$, $\lambda_c = 1\ \mu$, and $R_\ell = 10^6$ ohms, the minimum detectable carrier power for SNR = 10 is approximately 0.7×10^{-10} watts for m = 1.

Consider now the use of a photomultiplier as the optical detector. Here the internal gain G can be as high as 10^7. From Eqs. 4 and 5c one can see that the thermal noise term would then be reduced by a factor of 10^{14}. Thus, by using a photomultiplier, the thermal noise can be made insignificant. Suppose for the moment that thermal and dark current and background shot noises can be neglected relative to signal shot noise. In this case Eq. 6 applies, with P_o evaluated from Eq. 5a. Using $\lambda_c = 1$ micron, a value of n appropriate to a photomultiplier (n = 0.03 for an InGaAsP surface at 1 μ), SNR = 10, and m = 1 we find the minimum detectable carrier power ($4P_o$) in this case is approximately 0.7×10^{-12} watts. Thus one obtains two orders of magnitude more sensitivity relative to thermal noise limited operation.

In order to operate in the signal shot noise limited regime, one must limit the level of background light received, P_b, and the photomultiplier dark current, I_d. As can be seen from Eq. 4, the dark current must be small compared to the quantity I_o which equals 4×10^{-15} amperes for the values used above. Dark current can be minimized by using a small area photo surface and cooling the PM tube.

Again referring to Eq. 4, background shot noise can be eliminated if P_b is small compared to $P_o = 1.8 \times 10^{-13}$ watts, for the conditions assumed in calculating that value. Background light is minimized by using an optical bandpass filter which is matched to the band of the communication source and by limiting the receiver field of view to the minimum practical value.

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Table 4

Expression for background radiation power at detector surface

ırce lationship	Expression	Background Radiation Quantity
/ source	$P_b \doteq \frac{\pi\tau_a\tau_r\lambda_i d_r^2}{4} H(\lambda)$	Spectral irradiance
ıerical source ɔf diameter, d_s, ıot filling ·eceiver field ɔf view	$P_b = \frac{\pi\tau_a\tau_r\lambda_i d_s^2 d_r^2}{16L^2} W(\lambda)$	Spectral radiant emittance
	$P_b = \frac{\pi^2\tau_a\tau_r\lambda_i d_s^2 d_r^2}{16L^2} N(\lambda)$	Spectral radiance
	$P_b = \frac{\pi^2\tau_a\tau_r\lambda_i d_s^2 d_r^2 hf_c}{16L^2} Q(\lambda)$	Photon spectral radiance
:ended source ·illing receiver ·ield of view, θ_r	$P_b = \frac{\pi\tau_a\tau_r\lambda_i\theta_r^2 d_r^2}{4} W(\lambda)$	Spectral radiant emittance
	$P_b = \frac{\pi^2\tau_a\tau_r\lambda_i\theta_r^2 d_r^2}{4} N(\lambda)$	Spectral radiance
	$P_b = \frac{\pi^2\tau_a\tau_r\lambda_i\theta_r^2 d_r^2 hf_c}{4} Q(\lambda)$	Photon spectral radiance

:ation:

τ_a	Atmospheric transmissivity
τ_r	Receiver transmissivity
λ_i	Filter bandwidth
L	Transmitter-receiver distance
d_r	Receiver aperture diameter
d_s	Source diameter
θ_r	Receiver field of view whole angle at half-maximum

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Equation 18 may also be written in terms of the transmitted beam's divergence angle θ_b. Data on beam spread may be easier to obtain than data on the effective diffraction limiting aperture. For a circularly symmetric output beam, replace $(\lambda_c/d_t')^2$ by θ_b^2 ; and for a nonsymmetric beam by $\theta\|\theta\perp$, where $\theta\|\theta\perp$ are the beam divergences parallel and perpendicular to the laser junction respectively. Thus, if θ_b is used, we write

$$P_c = \frac{\pi^2}{8} P_s \frac{d_r^2}{\theta_b^2 L^2} \exp -\left\{\left(\frac{\pi}{2}\right)^2 \left(\frac{\alpha}{\theta_b}\right)^2\right\} \quad (18a)$$

The situation is very much different if one starts with an incoherent source of diameter d_s. Here the beam diameter at the receiver is much larger than the diffraction limited spot. Since the beam spread is much greater than that due to diffraction, one may use geometric optics and neglect diffraction. The best approach is to place the source at the focal plane of the transmitting lens so as to form its image at infinity. Thus, for distance L much greater than the transmitting lens focal length, one obtains an image of the source enlarged by a factor L/f where f is the focal length. For a lambertian emitter, and the receiver located within the beam, the collected power is given approximately by

$$P_c = \frac{P_s}{\pi} \left(\frac{d_r}{L}\right)^2 \left(\frac{d_t}{d_s}\right)^2 \cos\alpha \quad ; \quad \frac{d_t}{d_s} \le \frac{1}{\theta_b F_{min}} \quad (19)$$

where P_s is the total radiated power, P_s/π is the power per unit solid angle from the lambertian source, the quantity in square brackets is the solid angle of the receiver as seen from the transmitter, d_t^2/d_s^2 is a factor accounting for the collecting power of the transmitting lens, α is the angle by which the receiver is off-axis from the transmitter, θ_b is the full-angle beam spread (rad), and F_{min} is the minimum practical lens f-number (≈ 2). For example, an on-axis receiver with d_r = 10 cm, at 1 km distance from an LED with P_s = 1 mW, d_s = 0.5 mm, and a 2 mm diameter lens results in a value for P_c of 4×10^{-11} watts. Although Eq. 19 neglects transmission losses due to optics, windows, and the atmosphere, the collected power may yet exceed the minimum value (approximately 0.7×10^{-12} watts for m = 1.0) required for an SNR of 10 db under signal shot noise limited operation.

2.5 THE RANGE EQUATION

Having discussed the means of determining both signal and noise at the receiver, we are now in a position to derive the range equation: a formula permitting the calculation of maximum operating range given all the other system parameters.

For an incoherent source, we start with Eq. 19, which must be multiplied by the group of factors τ_a, τ_t, τ_r, τ_w, representing transmissivities of the atmosphere, the transmitter lens system, the receiver lens and optical filter, and any intervening windows respectively. Then solving for the range L, we find

$$L = \frac{d_r \cos\alpha}{d_s/d_t} \left(\frac{1}{4} \frac{P_s}{P_c} \tau_a \tau_t \tau_r \tau_w\right)^{1/2} \quad (20)$$

(incoherent source)

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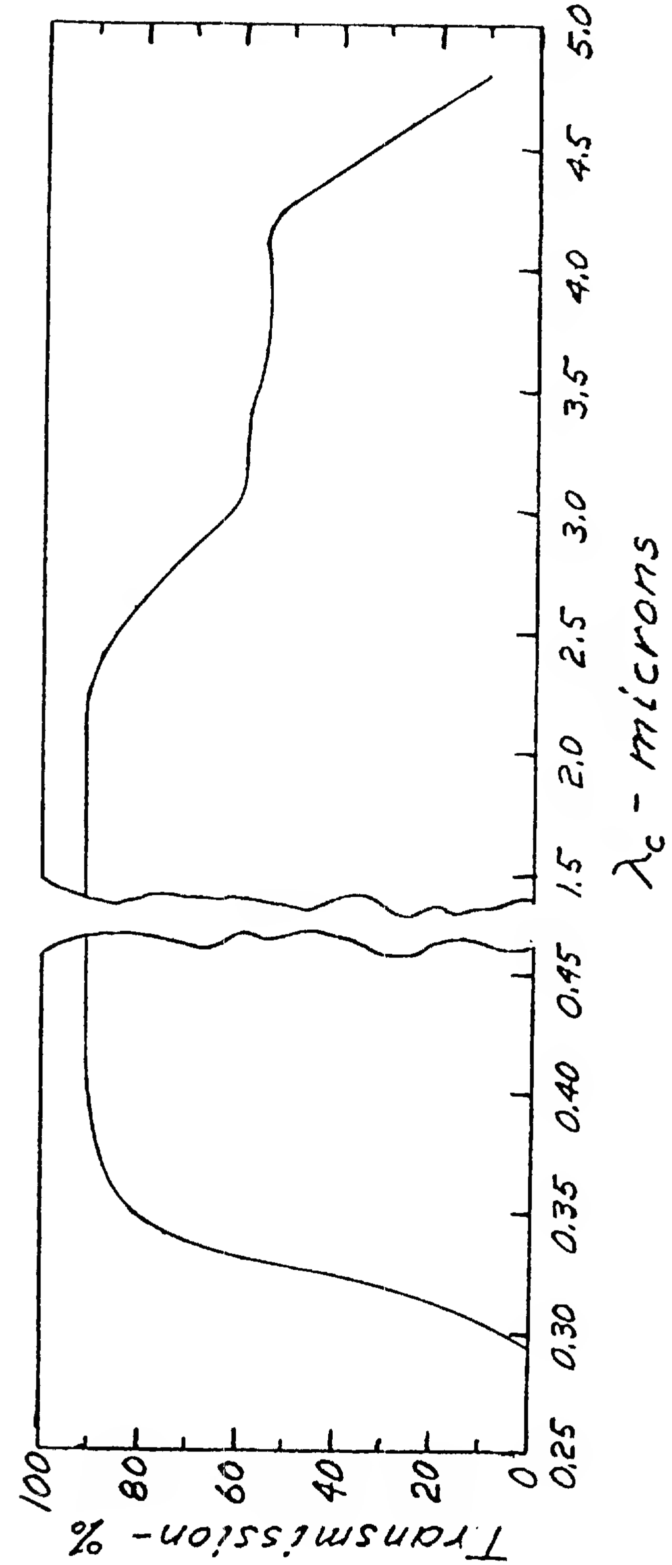

Figure 17. The transmittance of lime glass 1 mm thick

Thickness-Transmittance Nomograph

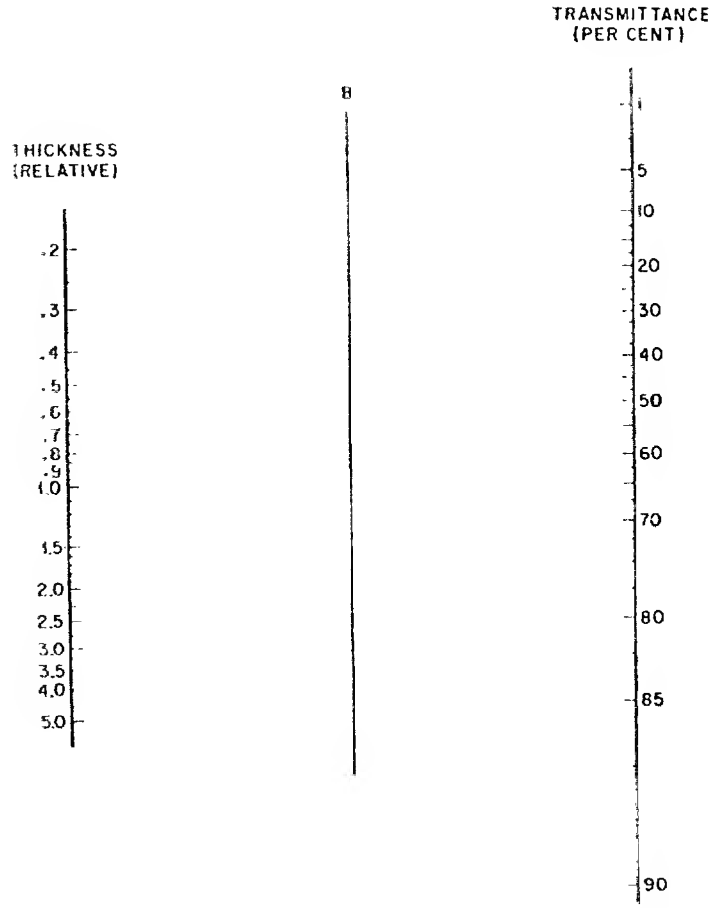

Figure 18. Nomograph for determining the change of transmission of a glass with a change of thickness. Scales are adjusted for a refractive index n = 1.50.

Example: At a wavelength of 400 mμ, the over-all transmittance of a glass 2 mm thick is 60 percent. What will be the transmittance of the same glass 3 mm thick? For a relative thickness of 1.0 and a transmission of 60 percent, an intercept is located on the B reference line. Using this same intercept and a relative thickness of 1.5, the corresponding transmittance value is then found to be 47 percent.

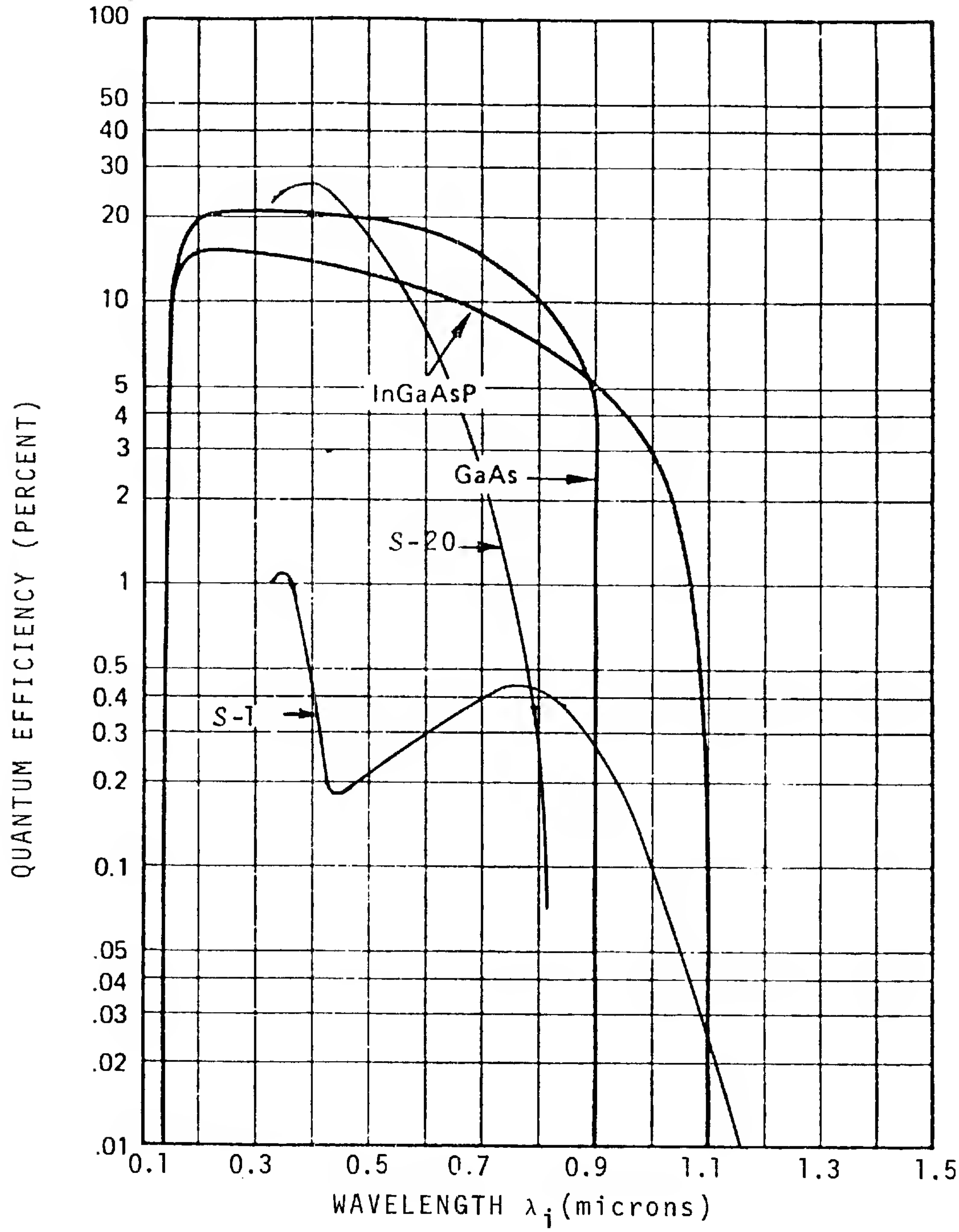

Figure 19. Quantum efficiency of photoemissive materials

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